

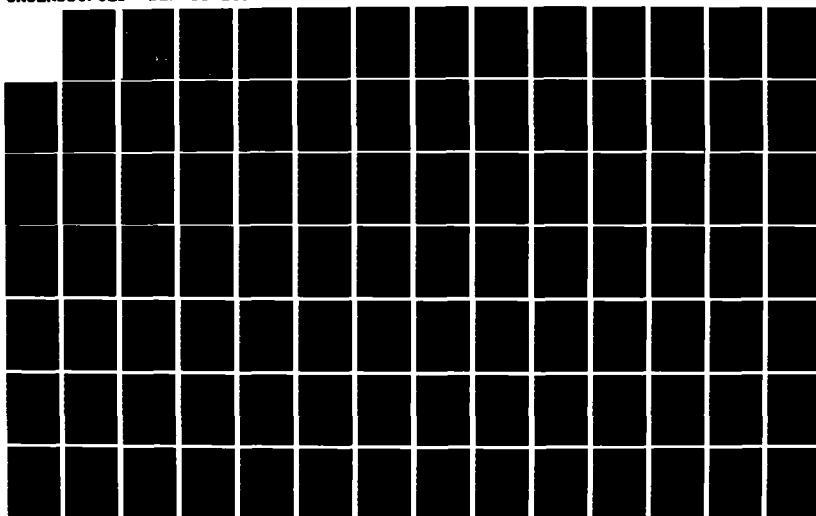
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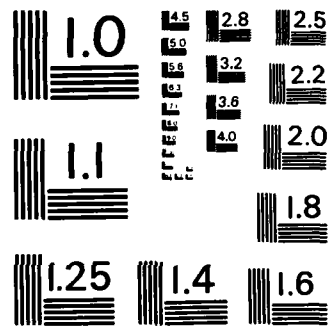
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**A METHODOLOGY FOR THE
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HUMAN INFORMATION
PROCESSING ORGANIZATIONS**

Kevin L. Boettcher

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by

Kevin L. Boettcher

This report is based on the unaltered thesis of Keven L. Boettcher submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the Massachusetts Institute of Technology in September 1985. This research was conducted at the M.I.T. Laboratory for Information and Decision Systems with support provided by the Office of Naval Research under grants ONR/N00014-77-C-0532 (NR 041-519) and ONR/N00014-84-K-0519 (NR 649-003).

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SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

DOCTOR OF PHILOSOPHY


at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(September 1985)

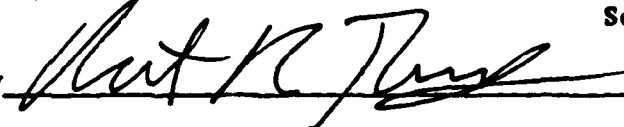
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**A METHODOLOGY FOR THE ANALYSIS AND DESIGN OF
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Kevin L. Boettcher

Submitted to the Department of Electrical Engineering and
Computer Science on September 17, 1985 in partial fulfillment
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ABSTRACT

The design of human organizations in which members perform routine tasks under the pressure of time is considered, particularly the problem of where and how in the design process to take into account human behavior and limitations. A three-phase design approach is suggested. In the first phase, the impact of human characteristics is neglected and attention is focused on aspects of organization structure that are external to individual members. An outcome of this phase is a set of normative decision rules that specify ideal human behavior. In the second phase, implementations for these decision rules are devised and models of actual human behavior and induced workload for the tasks established for each member are developed. The descriptions are determined as a function of parameters that relate to features of the task set-up and to the options provided to the member for accomplishing his task. A final design phase places these parameters for best organization performance and in view of the workload limitations of individual members. The result is an organization design.

The three-phase approach has been formalized as a multi-step methodology. Discussion and illustration is given for each design step. In addition, the methodology is exercised on a specific problem and the resulting organization design has been built. Operation of the organization has been tested under several conditions and experimentally observed results match those predicted for the design, which in turn supports the validity of the design approach.

Thesis Supervisor: Robert R. Tenney

Title: Assistant Professor of Electrical Engineering

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S. D. G.

I. INTRODUCTION

To accomplish tasks that are too large and complex for individuals, humans have devised and evolved a variety of organizational structures. These structures range from strict hierarchies to committees to matrices, and have been applied to manufacturing, governmental, and research tasks. Some structures are more suited to certain tasks than others, and this observation leads naturally to the analysis of organizational structures, with an eventual goal of purposeful design for specific tasks. Despite their proliferation, however, organizations have not readily yielded to the development of rigorous analysis and design techniques. This is due in part to the inherent complexity of situations where individuals are required to coordinate their efforts so that some overall goal is achieved. Another factor is the necessity to assess whether individuals within the organization are capable of doing their assigned jobs; that is, whether induced workload is within the limits of each member.

A goal of this thesis is to develop a framework and methodology for organization analysis and design that is appropriate for a particular class of organizations. Specifically, consideration is restricted to those organizations, or more generally, man-machine systems, that (a) involve human information processing tasks as integral to their operation, (b) incorporate a well-defined organizational goal held by all members (a team) and (c) have a short amount time available for individual information processing tasks, e.g. a few seconds or minutes. In addition, it is assumed that the overall task of the system is such that an individual cannot do it alone, that some form of coordination is required among organization members and that the information processing tasks are predominantly routine, i.e. are such that humans can be trained to execute them in a specified manner. Finally, the size of the organizations under consideration is taken to be small, say a few members.

As an example of the type of systems that are under investigation, consider a generic situation where control is desired for the enroute

aircraft within a particular geographical area. Such a situation is represented in Figure 1.1. Aircraft approach and pass through the

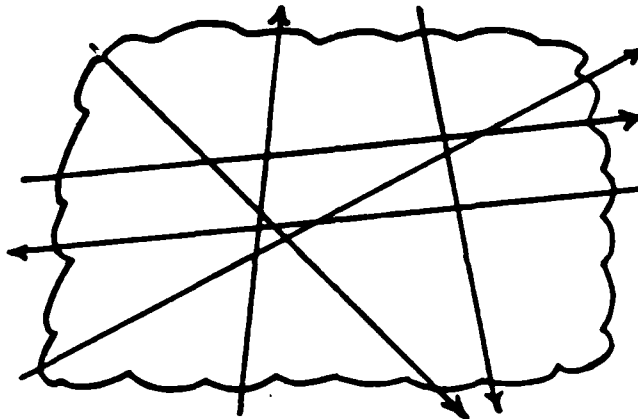


Figure 1.1 An Enroute Air Traffic Control Problem

geographical area, each with individual flight paths and speeds. The overall organizational goal is to maintain traffic separation with an extremely low near-miss probability. Furthermore, it is determined that humans are to be given this job, and that the situation requires more than one. Thus an organization is constituted, such as the one shown in Figure 1.2. Each organization member is given primary responsibility for a part

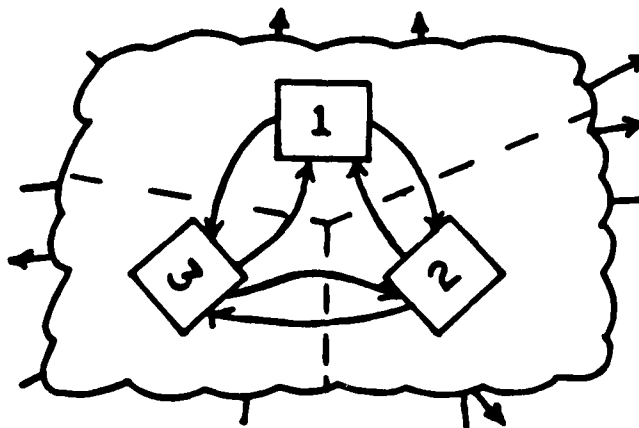


Figure 1.2 An Organization for Air Traffic Control

of the overall geographic region. He communicates directly to aircraft in

his region. However, as aircraft move from one area to the next, it is necessary for each controller to communicate to controllers of adjacent areas for purposes of coordination and smooth handoff of traffic. These tasks are primarily information processing ones; the controller is required to absorb information, either visual or auditory, and then use it to assess the situation and make appropriate responses that keep traffic flow orderly. Indeed, there is a minimum of creative activity in the sense of problem-solving. As part of the organization design, the controller is trained to recognize almost all situations which arise and to deal with them in a specific, well-defined manner. Finally, given the high speed and density of aircraft, controllers are under the pressure of time to process incoming information. Thus the situation is of the type under consideration in this thesis, and is one to which the methodology described in the following chapters could be applied.

Other examples of the type of organization under consideration can be found within the realm of military command, control, and communications systems, particularly those that operate in a tactical environment. There the common organization goal is often stated as a mission objective. Mission responsibilities are assigned to individual commanders. The ongoing battle requires that decisions be made quickly, but also in a coordinated manner so that the overall mission might be accomplished.

A question that is basic to the design of such systems is the partitioning of the overall system task so that it can be accomplished, not only satisfactorily according to some design criterion, but also with some assurance that human workload limitations will not be exceeded. As stated earlier, a goal of this thesis is to provide a method for analyzing and making any necessary tradeoffs between organization performance and human workload. The next sections outline the basic approach of the thesis toward this goal.

1.1 A Three-Phase View of Organization Design

Among the issues that must be resolved in the process of designing a human information processing organization is that of how, where, and to what extent in the process consideration of human characteristics and limitations should be included. At one extreme is the policy of dealing with the complexities of human behavior from the outset of the design process. At the other extreme is a policy of essentially neglecting the fact that humans will be part of the organization, and assuming that members will be able to perform any task that is assigned to them. The advantage of the former approach is that the design will likely be one in which individual member tasks are within workload limits. Arriving at such a design, however, involves consideration of the complexities of all aspects of human behavior at each design step. This can be tedious and time-consuming, and in the end largely unnecessary. On the other hand, an approach at the latter extreme offers the advantage of relative simplicity because a number of issues are neglected. There is no real assurance, however, that the final design will be realized as expected because of differences in actual human behavior from that which was desired or assumed.

There is considerable middle ground between these two extremes, and this thesis suggests a design approach that attempts to preserve some of the advantages of both, while minimizing the disadvantages. The basic idea is to separate design into three distinct parts, or phases. The first, a top-down phase, is one that neglects human limitations and focuses on other organization issues, such as basic structure and inter-member interactions. The second is a bottom-up phase, in which the complexities of human behavior are dealt with, but in a focused manner that considers only single parts of the organization and only directly relevant aspects of human behavior at a time. A third phase is needed to integrate the results of the first two and to ensure that they converge.

The three phase approach to organization design pursued in this thesis is illustrated in Figure 1.3. Given a (possibly general) statement

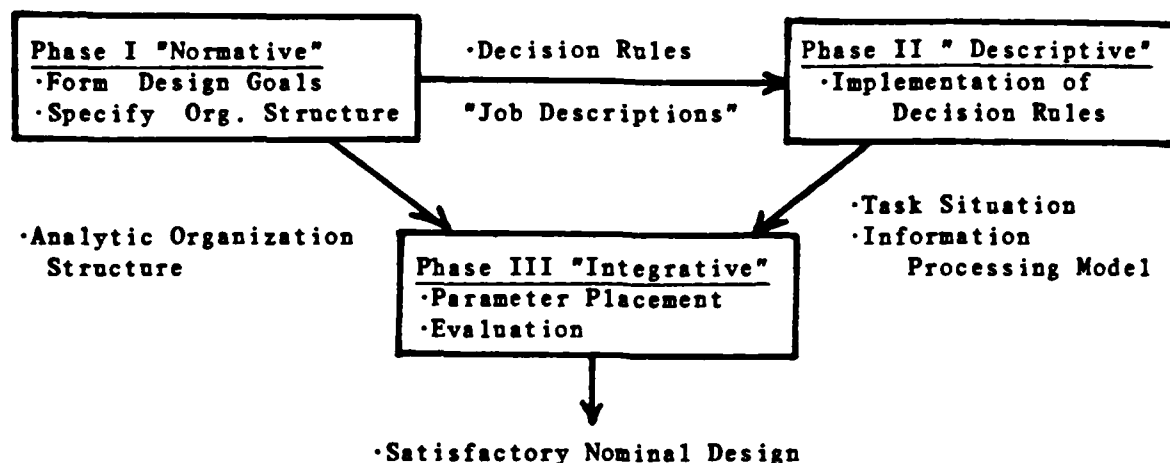


Figure 1.3 Three-Phase Organization Design Process

of the task for which an organization is desired, the first phase in the process establishes basic features of the organization structure and expresses them in analytic (i.e. mathematical) terms. Such features include the number of members, their interconnections and their respective protocols for interaction. Taken together, they constitute the analytic organization structure. A second aspect of Phase I is to determine how the inputs available to each member should be processed to generate outputs that may be passed to other members. This is done with respect to performance goals, and results in a set of decision rules that represent the desired behavior of each member. Phase I is thus normative in nature and yields job descriptions, in the form of decision rules, that serve as a target for actual human behavior.

Having determined, in the form of a decision rule, the information processing that each member ought to perform, the second phase of design aims to implement decision rules. "Implementation" refers to the specification of a collection of physical equipment, such as displays and response mechanisms, that the human is to use in order to accomplish the processing required by the decision rule. Also included is the immediate surroundings in which the equipment and the human are placed. Taken together, these elements are a member's task situation.

Given a task situation, a model is then developed that relates elements of the task situation to an organization member's actual behavior. This model, termed the information processing model, has two components. The first is a description of the actual input/output behavior realized. The second is a measure of the workload induced by task execution. Since humans are limited in their information processing ability, there will also be associated with this measure a characterization of the maximum workload allowable without overloading the member. In general, information processing descriptions will depend on settings of parameters that are part of the physical task set-up, that is, on task situation parameters. They will also be subject to variation due to the way an organization member chooses to perform his task, i.e. there will exist information processing parameters. Phase II is thus one that involves human modeling. As such it is labelled the descriptive phase in the design process. By first deriving a job description for each member, however, there exists a focus for both the specification and modeling of individual organization member tasks.

The first two phases of design result in distinct, though related, design elements. On the one hand is an analytic organization structure, which has been developed assuming ideal human behavior. On the other is a set of implementations of decision rules that have been constructed so that actual human behavior can match as closely as possible that which is desired. The match is not necessarily perfect, particularly given human workload limitations. Thus a third phase is necessary to integrate design elements in order to complete the organization design. In this phase the descriptions of actual input/output behavior are substituted for the decision rules in the analytic organization structure and the structure itself is augmented with the workload models. Then task situation and information processing parameters are placed, subject to constraints in the workload models, so that organization performance is optimized. The result is a nominal organization design that can be evaluated with respect to design goals. If the nominal design is determined to satisfy organization goals, then Phase III of the design process terminates, yielding a satisfactory nominal design.

The organization design approach incorporates both of the extremes possible for handling human behavior and limitations. Phase I essentially neglects the fact that humans will be part of the organization, except to define sets of inputs and sets of outputs and to determine desired transformations from inputs to outputs. Were the design process to terminate at this point, there would be no assurance that the decision rules obtained could be realized human by organization members; indeed, no physical means would have even been specified for them to try. Phase II addresses this issue and in so doing gives due consideration to the realities of human behavior, but the effort is focused on implementation of specific decision rules. Finally, Phase III brings the two extremes together, with the result that a design is obtained that has accounted for human behavior, but which has done so in a consistent and systematic manner. Note that, because of the separation into normative and descriptive phases made for pragmatic reasons, the design obtained is not truly optimal in the sense that the best possible combination of topological structure, physical equipment, human behavior, etc. has been assembled to accomplish some specific task. Rather, the design is one (of possibly many) that is acceptable with respect to design goals.

Key steps can be identified for successful execution of each design phase. These steps are formalized in the next section as a methodology for organization design.

1.2 A Methodology for Organization Design

Based on the three-phase approach to organization design, the methodology shown in Figure 1.4 has been devised. The following paragraphs briefly describe each methodology step. The purpose here is to provide an overview and to establish a conceptual framework and notation. More detailed discussion is contained in subsequent chapters, along with examples of execution of each methodology step.

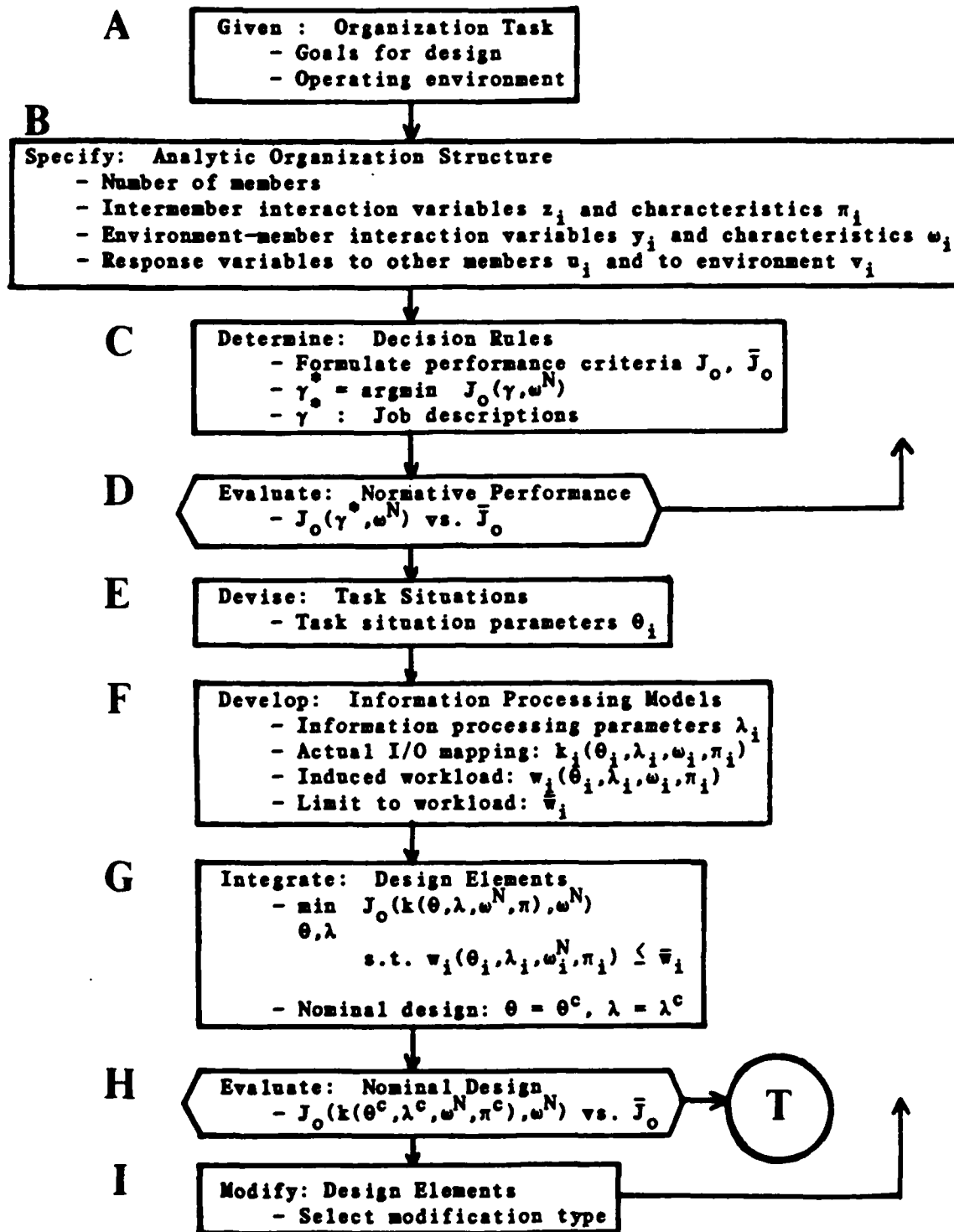


Figure 1.4 Organization Design Methodology

1.2.1 Phase I

Steps A-D in the methodology are part of Phase I. In Step A, the designer is presented with a task for which an organization is desired, along with statements of general objectives of the design and the expected organization operating environment. These statements are the point of departure for the design process. Subsequent choices in design will eventually be made and evaluated based on the designer's interpretation of them.

The first set of choices occurs in Step B, where an analytic organization structure is specified. Figure 1.5 illustrates in a conceptual way the elements of such a structure for a three-member organization. Members perform their tasks within their respective environments E_i . In general, however, aspects of an individual's environment can be held in common with other members, as indicated by the intersections of the E_i .

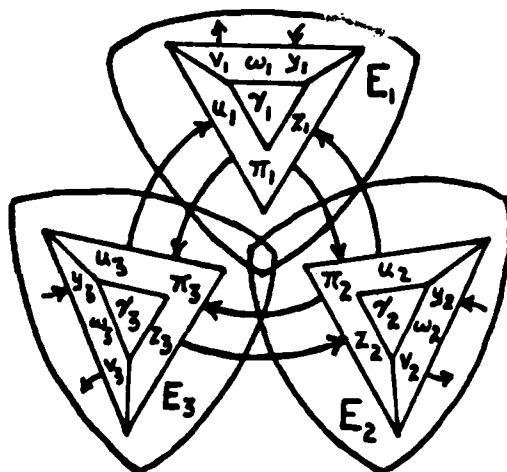


Figure 1.5 Concept of Analytic Organization Structure

Members receive interactions from two different sources. One is from their immediate environments as represented by the variables y_i . Characteristics of the environment that are relevant to these interactions are represented by the parameters ω_i . Interactions also arrive from other

organization members. These are represented by the variables z_i , and relevant characteristics of these interactions are represented by π_i . Included in ω_i and π_i are the statistical characteristics of the respective interaction variables. Organization members respond to their environments through the decision variables v_i and to other members through the decision variables u_i .

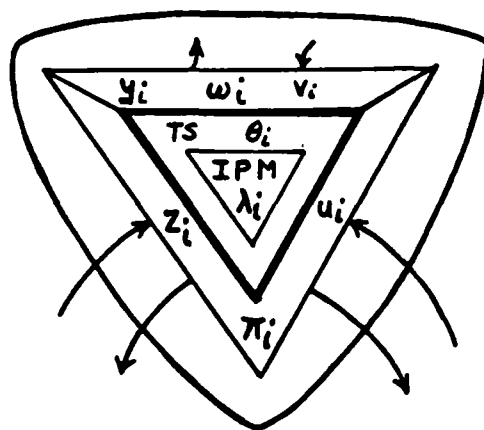
Thus in terms of Figure 1.5 the specification of an analytic organization structure includes the determination of the number of organization members and of the variables y_i , u_i , v_i , z_i . From the statement of the design problem, nominal values for the environmental parameters, ω_i^N , are also implied. All of this is done, of course, with the goal of accomplishing the overall information processing task of the organization.

A key element that is not specified in Step B is how individual members should respond when particular interactions are received. The determination of values for u_i and v_i from values of z_i and y_i is the information processing task of organization member i . This processing is abstractly represented by the mapping γ_i , selection of the desired mapping for member i is made in Step C. This is done with respect to the organization performance criterion J_0 , which has been formulated in view of design goals. J_0 must be expressed as a function of γ and ω , which collectively designate γ_i and ω_i , respectively. The optimal input/output mappings, designated γ^* and referred to as decision rules, are obtained by optimizing J_0 over γ , with ω fixed at its nominal value ω^N .

A final step in Phase I is Step D, which compares the performance obtained in Step C with that which is desired. If $J_0(\gamma^*, \omega^N)$ does not meet performance goals, then a revision in the organization structure is necessary.

1.2.2 Phase II

There are two methodology steps associated with Phase II. Recall that this phase accomplishes the implementation of decision rules. In terms of the formalism described above, the optimal input/output mappings γ^* , which represent ideal member behavior, are replaced with representations of actual behavior. This is illustrated for one organization member in Figure 1.6. The variables u_i , v_i , y_i , and z_i



TS: Task Situation
IPM: Information
Processing Model

Figure 1.6 Decision Rule Implementation

remain unchanged, as do w_i and π_i . However, a two-level structure has replaced γ_i , and each level is associated with a methodology step. In Step E, a task situation is devised for the decision rule. Associated with this physical setting are a number of parameters θ_i that represent characteristics of the situation that are to be determined at a later point in the design process.

For the task situation devised, an information processing model is developed in Step F of the methodology. In general, both elements of this model - an actual input/output mapping for the task situation and a workload measure - depend on the settings of parameters θ_i . Furthermore, they also depend on characteristics of the human organization member and the way he performs the information processing within his task. These characteristics are collectively represented by information processing parameters λ_i . Finally, the actual behavior realized by an organization

member will also in general be affected by environmental characteristics and the characteristics of inter-member interactions. As a result, the descriptions of input/output behavior, denoted by k_i , and workload, denoted by w_i , will be functions of θ_i , λ_i , ω_i , and π_i :

$$k_i = k_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad (1.1)$$

$$w_i = w_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad (1.2)$$

In addition, the workload element of the model will have associated with it a limit, or saturation point, denoted by \bar{w}_i .

1.2.3 Phase III

Given the organization design elements developed in Phases I and II, Step G accomplishes their integration by substituting k_i for γ_i^* in J_0 and adding the workload measures as constraints. Organization performance is then optimized by placing the task situation parameters θ and the information processing parameters λ with respect to performance and in view of workload limitations. The solution to this constrained optimization problem is given by θ^c and λ^c . With these quantities fixed as part of the organization structure, and with $\omega = \omega^N$, a nominal organization design results.

Step H evaluates the nominal design with respect to design goals. Such goals may, for example, impose requirements on organization operation when ω varies from ω^N . If all goals are satisfied, the methodology terminates. If the design is found to be unsatisfactory, then Step I is executed. In this latter step, a diagnostic function is performed, whereby the design's deficiencies are used to select particular modifications to be made in design elements. Depending on the type of modification selected, consideration then returns to a previous methodology step, and the design process iterates until a satisfactory nominal design is obtained.

1.3 Discussion

Subsequent chapters in the thesis discuss the methodology in detail. In this section an overview of the the main focus and themes of the thesis is given and further comments of a general nature are offered regarding the methodology and the viewpoint taken with respect to humans as part of organizations.

1.3.1 Overview of Thesis

Execution of the methodology described in the previous section touches on a number of complex questions and in general requires a great deal of judgement at each design step. Issues that can be raised cover a full spectrum, from the theoretical to the behavioral. In Phase I, for example, the modeling problem of defining interactions between decisionmakers is encountered, as well as the mathematical problem of solving for optimal team decision rules in a distributed setting. In Phase II, the designer is required to understand and quantitatively model human behavior, which is usually not straightforward in even the most unassuming situations. Finally, Phase III involves the mathematical solution of a complex, nonlinear, constrained optimization problem, which often poses difficulties.

While each methodology step is discussed in subsequent chapters and suggestions are made regarding its execution, the focus of the thesis is not in providing a general ready-to-use technique for organization design. This is well beyond the thesis scope. The main goal, however, is to provide a substantial argument for the methodology as an approach to organization design. The argument is made in part by discussing the methodology in general terms, by relating methodology steps to specific technical disciplines, and by indicating how methodology steps might be carried out in terms of specific classes of structures. An additional, and perhaps more convincing, aspect of the argument is that the

methodology has in fact been executed successfully on a specific design problem.

Thus the contribution of this thesis is twofold. First, it is the design methodology itself, or more precisely, the separation of the design process into normative, descriptive and integrative phases. This separation allows the designer to consider issues related to basic organization topology and structure without having to consider simultaneously human information processing behavior. Furthermore, the normative phase provides a focus, in the form of a job description, to guide the development of the information processing task for each member. The third, integrative phase provides for the synthesis, in a balanced way, of considerations of organization structure with considerations of human workload. In this phase the designer is able to view existing relationships between individual workload and organization performance and to explore various alternatives in trading one for the other. The ability to investigate and make such tradeoffs is a key advantage of the methodology.

A second aspect of the thesis contribution is that the design methodology's viability does not rest on conceptual arguments alone. It has, in fact, been used successfully to design an organization that has subsequently been tested and found to operate as expected. In particular, this provides support for the integrative phase of the design process, since this phase in effect must predict organization behavior in order to select the nominal design solution. The fact that such predictions are found to be valid provides evidence in support of the methodology's viability.

In support of the major themes of the thesis, a case study has been made of a specific team theoretic problem in which processing load descriptions for each member have been added. A constrained optimization problem has been formulated and solution properties have been characterized. Results of the investigation illuminate possible workload-performance relationships in a particular team structure. In addition,

the problem examined in the case study is a mathematical abstraction of the specific design example of the thesis and the results of the former have been used in support of the latter.

1.3.2 Humans as Organization Components

In this thesis, the point of view is taken that humans are to be regarded as components within a larger system. Such a viewpoint is analogous to that of investigators working with manual control problems, where the concept of a human operator transfer function is a familiar one (e.g. see [1]). Here, however, the essential function of the human is that of information processing. Furthermore, the tasks are assumed to be routine, i.e. not highly cognitive. Thus in the same sense that transfer functions characterize behavior in manual control tasks, input/output mappings will be used in the present context to characterize information processing tasks.

From the description of the methodology, it is evident that the decision rules that result from Phase I (the normative design phase) are well-defined. The question then arises as to whether the human is really necessary at all. That is, if the desired input/output behavior of each organization member is known as a solution to a well-formulated optimization problem, why not implement it in hardware or software (and by-pass Phases II and III)? To resolve this issue, one must look beyond the basic design methodology. The nominal organization design is appropriate for the specific organization task defined in Step A. However, a given organization may be required to perform many tasks, each of which spans a different period of time. For example, a command and control organization is called upon to carry out different missions depending on particular battle situations, high level commands issued, etc. In such a situation, the basic organization structure does not change; instead, the way it is used changes. Furthermore, the human components provide the adaptability required to make these changes. Thus, for a given organization task, the design that results from Steps A-I

ensures that the humans in the organization are able execute their respective individual tasks. The fact that humans are part of the organization permits the basic organization structure to switch to a different organization task, if necessary.

Another, and perhaps more compelling, reason for explicitly including humans is also dependent on their adaptability. While most of the information processing required for the types of organizations under consideration can be regarded as routine, there may be novel situations that arise occasionally. These require higher level human problem-solving skills in order to be resolved. It is in the event of these situations that humans have been included in the organization as "active components" in the first place. However, even though their main purpose is to handle unexpected situations, humans are also required to handle the routine situations that predominate as the organization accomplishes its task. This thesis is concerned with the problem of guaranteeing that the routine situations presented to the organization can be processed satisfactorily. The consideration of how an organization should process novel situations is beyond the scope of the present investigation.

1.3.3 Intended Position of Methodology in Design Process

The process of design proceeds by stages, from first conception to final implementation. The methodology outlined here for organization design is intended to be used at an early stage in the process. Phase I serves to test the basic feasibility of a particular organization structure. Phases II and III enlarge the scope of analysis to include considerations relating to the presence of humans within the organization. Once a satisfactory nominal design is obtained, however, the design process is not over. Subsequent steps, such as detailed simulation or prototype building and testing, will in general be necessary before final implementation is realized. The point here is that no claim is made that execution of the methodology will result in a "ready-to-use" design. Rather, the intended purpose is to occupy a place in the design process

where the scope of analytical consideration is extended to include, in some measure, human behavior. By incorporating descriptions of human behavior explicitly within an analytic framework, it is believed that valuable insight into likely organization behavior can be obtained for purposes of design.

1.4 Outline of Thesis

The thesis is organized as follows. Chapters two through four consider each of the three phases of organization design, beginning in chapter two with Phase I (Steps A-D) of the methodology. Chapter three considers Phase II (Steps E-F) and the third phase (Steps G-I) of design appears in chapter four.

Chapters two and three have a parallel structure. The first section in each discusses the corresponding methodology steps in a general way, elaborating further on their intended purpose. The second section establishes the relationship of these steps to the work of others. A third section delineates a particular class of organization structures or information processing models (as appropriate), and formally states how the methodology is applied to members of that class. Finally, an example is discussed that illustrates the execution of the methodology for the respective design phase under consideration.

Chapter four first considers each Phase III methodology step in a general way. A second section applies these steps to the particular example that was discussed in the previous two chapters.

Chapter five exercises the methodology on a specific design problem. The problem is stated at the outset of the chapter and each step of the methodology is executed in turn to arrive at an acceptable design. A laboratory implementation of the required task situations was used to operate the organization as designed, and to perform several tests to determine how closely the mathematical design predicts actual organization

behavior. In particular, it is demonstrated that failure to take human processing limitations into account can have dramatic effects, as well as that the careful placement of task situation and information processing parameters can be a meaningful and beneficial step in the design process.

Concluding comments and directions for future research are included in chapter six. Following this chapter, two appendices are attached that document the results of other investigations related to the thesis and that provide supporting material for discussion in the thesis body. In Appendix A, a specific team theoretic problem is investigated in which constraints that are reflective of workload have been added to each team member. Appendix B contains documentation for the experimental work done in developing and testing the organization design that is presented in chapter five.

II. ANALYTIC ORGANIZATION STRUCTURES - PHASE I

In this chapter, those steps of the methodology that are part of the top-down phase of organization design are discussed. These include the formulation of the design problem itself (Step A), the specification of an analytic organization structure (Step B), the determination of decision rules (Step C), and the evaluation of the analytic structure, given ideal behavior (Step D). The first section discusses each of these steps on a general level. Next, the execution of Steps A-D is placed in the context of related work. Of particular relevance here is the developing body of knowledge included under the rubrics of large-scale systems, team decision theory and decentralized control. Notions that have emerged from the study of organizations by management scientists are also appropriate. A third section considers a specific class of analytic organization structures, that of distributed detection networks, and discusses particular aspects of how Phase I of the methodology can be executed in the context of this class. Finally, a specific design situation is considered in the fourth section, to which Steps A-D of the methodology are applied.

2.1 Phase I Methodology Steps

In succeeding paragraphs of this section, each Phase I step in the methodology is considered. The discussion is presented on a conceptual level, with the goal of stating in broad terms some of the key aspects of each design step.

2.1.1 Formulation of Design Problem - Step A

There are two elements that are essential to a statement of the organization design problem: a description of the overall information processing task and a statement of the performance level expected. The

2.1.2 Specification of Analytic Organization Structure - Step B

The central function of Step B in the methodology is to translate the organization design objectives and the characteristics of the task defined in Step A into an analytic, i.e. mathematical form. This requires a number of choices by the designer. Among them are the number of organization members, their interconnection, and their protocols for interaction. Explicit evaluation of these choices is not made for every conceivable combination, but rather is made later in the context of evaluating selected overall organization designs, which occurs in Phase III. Even so, it is desirable to consider each choice in anticipation of its later impact on the organization.

With the goal of clarifying what is envisioned as an analytic organization structure, the following discussion offers a formalism within which to represent such structures. The viewpoint taken is similar to Tenney and Sandell [2]. Basically, organization members are viewed as processors of inputs into outputs. Inputs arrive from other members and through interactions with a local environment. They are processed into outputs that are sent back to other members or to the immediate environment. Governing this process is some temporal scheme for determining when responses are required or when interactions are to be sent. A characteristic that is central for the present development, however, is that each member must on a regular basis select outputs as responses to current inputs. In specifying an analytic organization structure, all aspects of organization operation are to be defined, except for this latter association of response values to input values.

The above can be stated more formally. Once the number of organization members has been determined by the designer, the overall organization task is divided among those members, and the design proceeds by identifying specific mechanisms for how each member is to interact with his respective environment and with other members. The variables y_i and v_i are specified to represent member i 's interactions with his environment (refer to Figure 1.5). Also specified are the sets from which variable

values are drawn:

$$y_i \in Y_i \quad (2.1)$$

$$v_i \in V_i \quad (2.2)$$

Included as part of the environment-member interaction variables is the delineation of a set of generalized parameters that characterize the environment of the member. These might include the relative likelihood that certain events will occur in the environment, the tempo of the member's interactions with his environment, or simply the probability distribution on environmental interaction variables. Parameter values are drawn from a set specified by the designer, i.e.

$$\omega_i \in \Omega_i \quad (2.3)$$

The purpose in defining ω_i as an element of structure is to formalize the notion that the organization's environment is either not known precisely or is subject to change as the organization operates. Assessing the sensitivity of the organization design to such uncertainty is thus an important consideration.

Inter-member interactions that the designer specifies are represented in a similar manner. The variables z_i are the interactions that arrive from other members. Responses forwarded to other members are designated by the variables u_i . Their respective values are drawn from sets specified by the designer:

$$z_i \in Z_i \quad (2.4)$$

$$u_i \in U_i \quad (2.5)$$

As a matter of definition, it may be useful to partition z_i and u_i according to the particular member with which they represent an interaction, i.e. z_{ij} designates interactions arriving to member i from member j .

Just as ω_i is intended to capture characteristics of interactions with the environment, π_i is a set of generalized parameters that characterize inter-member interactions. The key aspect of π_i is that it designates characteristics of interactions as member i experiences them. Thus while explicit parameters of organization structure can be part of π_i , such as a deadline for responding to another member, it is also possible that quantities that are induced as a consequence of organization operation, such as the probability distribution on the set Z_i , can be included as part of π_i . The main purpose in defining π_i as an element of structure is to provide a formalism for later use in the methodology, where not only the values of interaction variables affect human information processing, but also the characteristics of how these variables arrive for processing. Since such characteristics depend in general on the processing accomplished by other members, which is itself subject to change, it is convenient to lump the collective effects of such variation into a single quantity π_i that is developed from member i 's point of view. As with ω_i , π_i is considered to take values from a specified set:

$$\pi_i \in \Pi_i \quad (2.6)$$

The actual value of π_i is induced as a consequence of the particular design selected.

In terms of the formalism introduced above, in Step B the designer must specify the variables z_i , u_i , v_i , and y_i and their respective sets of possible values. The generalized parameters included in ω_i and π_i must also be defined, along with the sets Ω_i and Π_i . Furthermore, nominal values for ω_i , denoted ω_i^N , are to be selected. The only aspect of the organization structure that has not been specified at this point is the mapping from inputs to outputs for each member. That is, the relationship between $Z_i \times Y_i$ and $V_i \times U_i$ is not defined. Such a relationship is designated as an input/output mapping γ_i , where in general γ_i is selected from the set Γ_i :

$$\gamma_i \in \Gamma_i = \{\gamma_i \mid Z_i \times Y_i \rightarrow p(V_i \times U_i)\} \quad (2.7)$$

That is, γ_i maps possible values of z_i and y_i into distributions on possible values of v_i and u_i . Once γ_i is selected and inserted into the analytic organization structure a working analytic model is obtained.

The formalism used to discuss analytic organization structures is not intended to be rigorous. There are a number of issues that have not been addressed and which will require considerable effort on the part of the designer in deciding an analytic organization structure. These include, for example, the basic question of how to partition an overall task into subtasks that are appropriate for individual members, as well as the selection of a particular temporal framework which governs organization dynamics. However, the formalism highlights the major issues that are of concern in the present context. Specifically, Step B should bring the design to the point where what remains is to determine for each member which input should be mapped to which output, and in what sense (deterministically or probabilistically). In addition, the characteristics ω_i and π_i identified at this point will be used later in the design process when humans are included explicitly.

2.1.3 Determination of Decision Rules - Step C

To complete the specification of a working analytic organization model, it is necessary to select the input/output mappings to be used by each member. This is done in Step C of the methodology by solving an optimization problem. The criterion to be optimized is first formulated to reflect the design goals stated in Step A is expressed in terms of a cost J_0 . Given that all other elements of the analytic organization structure have been specified except γ , J_0 need only be stated explicitly as a function of γ . However, in view of the uncertainty in the organization's environment represented by ω , it is useful to show explicitly the dependence of J_0 on ω , although for purposes of selecting the desired input/output mappings ω is fixed at its nominal value. Thus the problem to be solved is stated formally as

Decision Rule Problem (DR)

$$\begin{array}{l} \min J_0(\gamma, \omega^N) \\ \gamma \in \Gamma \end{array}$$

The solution to Problem DR yields an optimal input/output mapping γ_i^* for each member, which is designated as a decision rule. Decision rules are the key link between the purely analytical consideration of the organization in Phase I with the consideration of actual human behavior in Phase II. Decision rules are effectively the job descriptions that are given to organization members, and thus serve as a prescription for ideal human behavior.

It is important to note that a globally optimal solution of Problem DR is not necessary as a requirement of the methodology. Recall that the primary objective is that, an organization design be obtained that meets design goals, particularly the performance level that was specified in Step A. More than one set of decision rules may meet this objective, and some may be easier than others to obtain analytically as solutions to Problem DR. Thus the approach taken in solving Problem DR has a degree of flexibility and choice associated with it, and the designer may well elect to terminate the search short of obtaining a global minimum solution.

In view of the fact that human limitations in information processing are a primary concern in this thesis, the question arises as to whether the problem formulated in Step C might be modified to include workload considerations as constraints. Such a formulation is indeed fundamental to the approach pursued in the thesis, but it is inappropriate to pursue it at this point. Decision rules are mathematical descriptions of the desired behavior of a particular system component. Workload, however, describes human information processing in a specific physical situation. Workload is thus dependent on the physical implementation of a decision rule. To include a workload constraint at Step C would in effect presume that a description of the workload for a given decision rule could be

specified independently of its implementation, or that a physical implementation could be selected without knowledge of the desired decision rule. This is not possible. This is why the methodology separates these two issues. First, the desired behavior is determined, apart from the ability of humans to actually accomplish it (Phase I). Then consideration is given to how such behavior can be realized (Phase II).

2.1.4 Evaluation of Basic Organization Structure - Step D

By substituting the decision rules obtained as solutions in Step C into the organization structure developed in Step B, a working analytic model of the organization results. This model represents in some sense the "best" outcome that could be expected as a design, given the basic organization structure. That is, subsequent steps in design will at best only be able to reproduce exactly the decision rules γ^* as the actual input/output behavior of organization members. Moreover, it is not likely in general that γ^* will be realized perfectly. Thus performance of the organization will not be any better than that which is predicted from purely analytical considerations, and will likely be worse because of later compromises made due to human workload limitations. It is therefore useful at this point to compare the analytic organization model with design goals, and evaluate whether it is possible for the basic structure to result in an acceptable design. This is the function of Step D in the methodology.

The assessment made in Step D is limited to a single definite conclusion: if the analytic organization, operating with its decision rules, does not meet design objectives as outlined in Step A, then an alternate structure is necessary. If such a conclusion is reached, the designer must re-consider some of the choices made in Step B. Ideally, the points at which the design is inadequate will lead the designer to select specific modifications to make in organization structure.

If, on the other hand, the analytic organization does meet design

goals at this point, there is no guarantee that subsequent implementation of decision rules will result in a nominal design which is also acceptable. However, preliminary indication of how likely it is that the organization structure will remain viable might be obtained by evaluating the sensitivity of J_0 to variation in ω when $\gamma = \gamma^*$. That is, if it is assumed that the actual input/output behavior realized by organization members will approximate γ^* , then it might be useful to evaluate

$$\frac{\partial J_0(\gamma^*, \omega)}{\partial \omega}$$

to obtain an indication of whether the general operating region that is unfolding for the organization is in fact a satisfactory one in view of uncertainties about the operating environment.

In general, Step D represents an opportunity to assess the design at an intermediate stage in its development. A considerable amount of effort has been expended in Steps B and C, and Phase II will be another major step in the design process. Step D is the bridge between these two efforts and can be used as convenient milestone in the design process.

2.2 Approaches to Phase I Execution

This section describes the relationship between the concepts relevant to Phase I and other work. Though satisfactory completion of Phase I is not tied necessarily to a particular analytic framework, the issues that the designer must consider in the present context are similar to those considered by Tenney and Sandell [2],[3].

Another framework that is complementary to Phase I considerations is that of team theory. A team-theoretic decision problem has five essential features [4]: (a) an underlying uncertainty expressed as a vector of random variables; (b) a set of observations that are functions of the uncertainty vector; (c) a set of decision variables—one per decision-maker (team member); (d) a set of decision rules—one per team member—

which select a value of the decision variable based on the observations available; and (e) a criterion that assigns costs according to the actual values taken by the random vector and the decision variable of each team member.

In terms of the steps within Phase I, (a)-(c) correspond to the specification of an analytic organization structure in Step B. The underlying uncertainty (a) and the observations available (b) determine the environment in which the team operates. Characterization of this environment in terms of a set of parameters corresponds to specification of ω . Available observations and decision variables (b-c) are the inputs (z, y) and outputs (u, v) of organization members, respectively, and the set of decision rules (d) corresponds directly to the set γ^* . Selection of a decision rule in a team-theoretic problem is done with respect to minimizing the cost criterion (e). This corresponds to the minimization of J_0 in Step C. Finally, the underlying notion in team decision theory is that all members are cooperating to the fullest extent for benefit of the overall team (common cost criterion). This is also consistent with the class of organizations under consideration in this thesis.

Solutions for decision rules in team problems are characterized by the nature of the problem's information structure. There exist solutions for classical [5] and partially-nested [6] structures. Recently, solution has been obtained for a class of non-partially-nested information structures [7]. Thus results and methods drawn from the investigation of team decision problems provide an approach to the execution of Phase I.

Other approaches to executing Phase I can be found within the broader consideration of large-scale systems. [8] surveys the literature on methods for decentralized control and the analysis of large-scale systems. These methods are to be considered as a resource upon which to draw. In this sense, the designer is free to use any technique that results in "job descriptions" for individual organization members, but which also satisfies the necessity to assess overall organization performance.

Large-scale systems and team-theoretic analyses do not explicitly consider humans as implementing decision rules. In fact, the implicit assumption is of perfect rationality [9], which humans do not exhibit in organizations [10]. The study of actual human organizations, though largely qualitative, can provide guidance for the execution of Phase I. That is, even though explicit consideration of workload is not possible in Phase I in the sense of a mathematical formulation, it may be possible, knowing that humans will eventually be a factor in the analysis, to incorporate principles of human organization design when the analytic organization structure is specified. It may then be easier to realize the decision rules that result in Step C. Among recent qualitative work in organization design, Galbraith [11] analyzes organizations in terms of information flow and processing, and describes other concepts that are related to the present work.

Finally, some work has been done to simulate and analyze organization behavior [12]. Other work has used experiments with different organization structures as a basis for abstracting principles of organization [13]. Still other investigators have described principles for decentralized decisionmaking by analogy with observed human behavior in a situation requiring negotiation [14]. Thus there exists a variety of paradigms and principles, both qualitative and quantitative, from which one can draw in order to specify an analytic organization structure.

2.3 A Class of Analytic Organization Structures

To illustrate the steps executed in Phase I of the design process, this section considers a specific class of analytic organization structures, the so-called distributed detection network (DDN) [7]. Formulation of this class has been motivated by the situation where a surveillance task is to be executed using a number of geographically separated sensors that are able to make observations on the same phenomenon, but which are limited in their ability to communicate with each other. Characteristics of a DDN include an underlying phenomenon

whose state is uncertain, noisy observations made at each node in the network as to its value, and an acyclic node interconnection topology that contains at most one path from any one node to another. The task of the network is to reach a decision as to the state of the phenomenon and to do so optimally with respect to given error penalties. This task is accomplished by providing each node with a decision rule that specifies the contents of messages to be sent to other, adjacent nodes when particular observations and messages have been received.

The following paragraphs briefly review the characteristics of a DDN and discuss the execution of Phase I, particularly Steps B and C, in terms of this class. Though presented here as an example, DDN are in fact one of a very few classes of analytic structures for which the mathematics exist to make Step C possible. Indeed, this reality is a limiting factor in the applicability of the design approach presented in this thesis.

2.3.1 Elements of DDN Structure

A distributed detection network is characterized by several features as follows. The underlying phenomenon, denoted H , is static and can take a discrete number of values. These values are known and can be represented as a set of M possible hypotheses, whose a priori statistics are also known. That is,

$$H = H^k \text{ w.p. } p(H=H^k) , i = 1, \dots, M \quad (2.8)$$

There are available N noisy observations y_i on the underlying hypothesis, which are conditionally statistically independent, i.e.

$$p(y_i | y_1, y_2, \dots, y_{i-1}, y_{i+1}, \dots, y_N, H) = p(y_i | H) \quad \forall i \quad (2.9)$$

By assumption, these observations are distributed in some sense with respect to each other and are the basis for defining the nodes in a DDN.

The interconnection topology between nodes in a DDN is that of a singly-connected network. In graph theoretic terms, such a network is an acyclic directed graph that contains at most one distinct directed edge between any pair of nodes. Transmission on interconnecting links is assumed to be error-free. In addition, there is a finite number of symbols available for use on a given link. This latter assumption models the limited bandwidth condition that is a key issue with respect to a DDN.

Given this structure, a DDN node is defined using three basic operators, which are illustrated in Figure 2.1. A tandem operator (a)

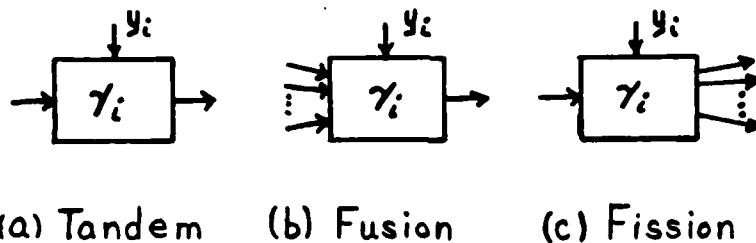


Figure 2.1 Basic DDN Operators

receives messages from one node and sends messages to a single destination. Fusion operators (b) receive from many nodes and send to a single destination, and fission operators (c) receive from one node but send to many destinations. Each operator has an observation y_i associated with it. Given the particular input messages and the observation y_i , the determination of which output messages should be sent is made using the mapping γ_i . It is possible to combine fission and fusion operators at a single node, and it is also possible that a node will have no input messages. This latter type of node is referred to as a source node.

The singly-connected structure of a DDN induces a partial ordering on events within the network. It is assumed that all nodes receive their respective observations y_i simultaneously. Observations are then incorporated with incoming messages at each node to obtain outgoing messages. Each node must therefore wait for the arrival of messages from nodes that

precede it in the partial ordering of events. Because they receive no messages, source nodes are thus the first nodes to complete their respective processing.

Relationship of DDN to Step B

To illustrate how a DDN can be used as an analytic organization structure, consider the four-node DDN shown in Figure 2.2. Two tandem

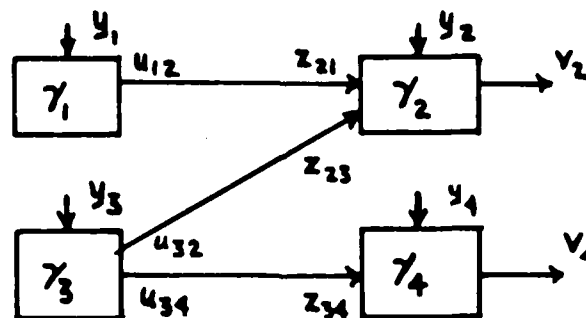


Figure 2.2 A Four Node DDN

operators and one fusion and one fission operator have been used to form the network. There are two source nodes in the network. In order to facilitate the correspondence between a DDN and an analytic organization structure, the formalism introduced in the previous section has been used to label the links between nodes.

In the network shown, the ordering of events is as follows. After observations have arrived at each node, nodes 1 and 3 select their output message symbols for transmission, which are the values of variables u_{12} , and u_{32} , u_{34} , respectively. These messages are then transmitted to nodes 2 and 4 and received as the variables z_{21} , z_{23} , and z_{43} . Finally, at nodes 2 and 4 values are selected for v_2 and v_4 using the observations y_2 , y_4 and the received interactions. Note that because transmission on links is error-free, it is true that

$$u_{12} = z_{21} \quad (2.10)$$

$$u_{32} = z_{23} \quad (2.11)$$

$$u_{34} = z_{43} \quad (2.12)$$

For the DDN in Figure 2.2 to be an analytic organization structure, the design must specify the following:

$$\text{sets: } U_{1,2}, U_{2,2}, U_{3,4}, V_2, V_4 \quad (2.13)$$

$$\text{distributions: } p(y_i|H) \quad i = 1,4 \quad (2.14)$$

$$p(H) \quad (2.15)$$

Eq.(2.13), (2.14), and (2.15), along with the properties of the DDN structure already discussed, completely specify the operation of the network, except for determining the association of output symbols to input symbols and observations. That is, what remains to be specified is the complement of input/output mappings γ_i , $i = 1,4$ where

$$\gamma_1 \in \Gamma_1 = \{\gamma_1 | Y_1 \rightarrow p(U_{1,2})\} \quad (2.16)$$

$$\gamma_2 \in \Gamma_2 = \{\gamma_2 | Y_2 \times Z_{2,1} \times Z_{2,2} \rightarrow p(V_2)\} \quad (2.17)$$

$$\gamma_3 \in \Gamma_3 = \{\gamma_3 | Y_3 \rightarrow p(U_{3,1}, U_{3,4})\} \quad (2.18)$$

$$\gamma_4 \in \Gamma_4 = \{\gamma_4 | Y_4 \times Z_{4,1} \rightarrow p(V_4)\} \quad (2.19)$$

Furthermore, if the structure in Figure 2.2 is to be used as an analytic organization structure, the designer would also specify the generalized parameters ω_i and π_i . In the present case ω_i might be the distributions $p(y_i|H)$, or it might be particular characteristics of a distribution type, such as mean and variance. Similarly, the distribution on Z_{ij} might be included in π_i .

2.3.2 DDN Decision Rules

In a DDN, the mappings γ_i are selected to optimize the performance of the network. To do this a cost is assessed locally at each node, and the total cost is minimized using a technique based on spatial dynamic programming. The result is a set of optimal input/output mappings γ_i^* . Stated in terms of the DDN in Figure 2.2, there are four cost functions

J_i , one at each node:

$$J_1 = J_1(y_1, u_1) \quad (2.20)$$

$$J_2 = J_2(y_2, z_2, v_2) \quad (2.21)$$

$$J_3 = J_3(y_3, u_3) \quad (2.22)$$

$$J_4 = J_4(y_4, z_4, v_4) \quad (2.23)$$

The optimal mappings are those that minimize the expected value of the total cost J :

Problem - DDN Decision Rules (DR-DDN)

$$\min_{\gamma_i \in \Gamma_i} \{ E(J) \} = \min_{\gamma_i \in \Gamma_i} \left\{ E \sum_{i=1}^4 \{ J_i \} \right\}$$

The technique for finding DDN decision rules uses the additive cost structure to decompose the overall problem into a series of stagewise minimizations. The solution technique also depends on two other properties of the the DDN structure. One is that for any two nodes connected by a link, their analytic relationship is completely characterized by the joint probability distribution on the values of H and on the set of symbols that can be transmitted over the link. In terms of the DDN in Figure 2.2, the distributions $p(u_{1,2}, H)$, $p(u_{2,3}, H)$ and $p(u_{3,4}, H)$ completely summarize the relationships between the nodes.

A second property of a DDN that is exploited derives from its singly-connected topology. Because of this characteristic, it is possible to define a "sweep pattern" for the network that is such that each link is traversed exactly once (possibly opposite its actual direction) and also such that the partial ordering on events in the network is preserved.

Taken together, these three features of a DDN and its cost structure can be used to solve for decision rules. Basically, the solution technique uses the established sweep pattern to transfer the per node costs through the network. This is done by finding the minimizing γ_i at a

node and then traversing a link to the next node via the joint distribution associated with that link. For the network in Figure 2.2, this might be executed as follows. Beginning at node 4, it is possible to minimize $E[J_4]$ over γ_4 as a function of $p(z_{4,4}, H)$. Sweeping back to node 3, a minimization is conducted over γ_3 as a function of $p(u_{3,3}, H)$. Not only is the expected cost at node 3 considered, but the added cost that will accrue at node 4 is also taken into account. Since in the first optimization stage the minimum cost at node 4 has been found as a function of $p(z_{4,4}, H)$, it is necessary in the second stage to only consider how the selection of γ_3 affects the value of $p(z_{4,4}, H)$. This process continues until all nodes have been considered and all links traversed.

The basic feature of the solution technique is that at each stage n in the process there is a problem to solve of the form

$$V_n^*(P_n) = \min_{\gamma_i} \left\{ E\{\bar{J}_i + V_{n+1}^*(P_{n+1})\} \right\} \quad (2.24)$$

At stage n , the input/output mapping at node i is under explicit consideration. \bar{J}_i is a reformulated version of J_i used in the optimization technique. P_{n+1} represents the joint distribution on the link that has just been traversed to reach the node and P_n is the joint distribution on the link that will be traversed to reach the next node in the sweep pattern. V_{n+1}^* is the equivalent of the optimal cost-to-go in a dynamic programming formulation. Here it represents the optimal cost to retrace the sweep pattern back to its origin. In general, the number of stages n is greater by 1 than the number of nodes. The additional stage does not involve an input/output mapping, and is analogous to the terminal stage in a dynamic programming formulation. Solution to the problem in eq.(2.24) finds the optimal input/output mapping γ_i^* as a function of P_n . When the last node in the sweep pattern is reached, a reverse pass will select which of the γ_i^* is to be the decision rule at the i^{th} node.

The discussion here of the solution for DDN decision rules is intended to be an overview only. The technique described entails the reformulation of the stochastic optimization problem as given by Problem

DR-DDN into an equivalent deterministic problem. For the details of how this is done and for how sweep patterns are established, see [7]. For present purposes, it is sufficient to note that decision rules can be obtained for a DDN and that the essential features of the solution technique are a stagewise minimization that is performed in terms of the joint distribution on each link variable and the underlying phenomenon H.

Relationship to Step C

Given the association made earlier between a DDN structure and an analytic organization structure, it is straightforward to complete this association as it applies to Step C considerations. Basically, the decision rule mappings in a DDN directly correspond to those that are desired as the outcome of Step C. Thus, if a per member cost structure is assigned to the analytic organization structure the technique for finding decision rules described above can be used to determine job descriptions for organization members.

2.4 Execution of Phase I - Example

To further demonstrate what is intended in Phase I of the methodology, a specific design problem is considered in this section. After stating the problem, the remaining steps in Phase I are then executed, with the result that a promising analytic organization structure emerges. Since the structure is of the distributed detection network class, the discussion in the previous section is directly applicable.

2.4.1 Statement of Design Problem - Step A

The manufacturing process for a certain crystalline material results in crystalline structures of two types. One of these types is the structure desired for the material and the other has properties that make it unusable. The process produces the material in wafers, and is such

that a given wafer will have a predominantly uniform crystalline structure. About 20% of the wafers manufactured are unusable, although this figure is known to be as low as 15% or as high as 25%, depending on the current batch.

It is desired to sort the defective wafers from the usable ones and to do so with an error rate of less than 10%. Furthermore, physical limitations dictate that the inspection and sorting must take place as wafers move from manufacturing to assembly along a conveyor belt. Wafers are carried on the belt at the rate of R per minute. This rate is nominally at R_0 but is subject to a $\pm 10\%$ variation.

The basic test for determining the crystalline structure type involves irradiating the wafer and then observing the diffraction pattern that obtains. Because of impurities in the material and also due to the mechanics of the test equipment, the diffraction image does not unambiguously register crystalline structure. Instead, the orientation of the image is used as an indication of crystalline type. The judgement required in assessing image orientation is not readily automated, and the test therefore depends on human capabilities in order to be successful.

2.4.2 Analytic Organization Structure - Step B

The design problem posed is essentially one of devising an inspection scheme for sorting wafers as they move along a conveyor. Furthermore, because of the nature of the test, humans are required as part of the scheme. Thus the designer must determine the rate at which humans can reliably execute diffraction judgements and compare it with the conveyor belt speed. Assume that no individual can alone perform the inspections fast enough and still meet performance requirements. An inspection team must then be formed such that the individually inadequate capabilities of members are aggregated advantageously to meet performance requirements. In doing so, additional consideration must be given to coordinating the efforts of team members. Many inspection schemes are possible. A

reasonable next step is to propose an organization structure for the inspection test and to analyze it with respect to design requirements.

Consider the inspection scheme shown in Figure 2.3. Two diffraction

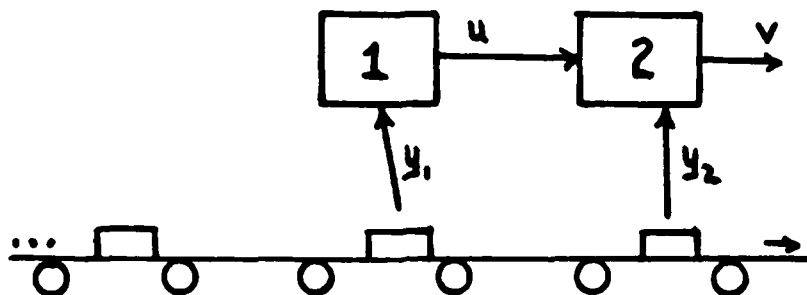


Figure 2.3 Wafer Inspection Scheme

tests are applied to each wafer, one after the other. The diffraction image obtained on each test is designated by y . Based on y_1 , the first test is used to give a preliminary indication of the crystalline type. This indication is passed to the second inspection test station as the message u . This message is then to be incorporated with the second diffraction pattern to determine whether the wafer should be declared unusable. The value of v represents the decision to remove the wafer from the conveyor. The tests at each station are arranged so that the second test is being performed on one wafer while the first test is being applied to the wafer that follows it on the belt. This is accomplished with no confusion in the signal sent from the first test station to the second. That is, the value of u used in the second test always corresponds to the wafer currently under test.

To complete the specification of the scheme in Figure 2.3, additional modeling assumptions are necessary about the characteristics of the tests. A representative diffraction image is shown in Figure 2.4. As noted earlier, discrimination between crystalline structures is made according to the general orientation of the image. Let ρ be the orientation angle as shown in Figure 2.4. Assume that if the diffraction test were a



Figure 2.4 Representative Diffraction Pattern

perfect indication of crystalline structure, it would show good wafers at angle $\rho_1 = 135^\circ$ and bad wafers at $\rho_0 = 45^\circ$.

Denote by H^k ($k = 0,1$) the event that a given wafer is unusable or usable, respectively. Then according to the characteristics of the manufacturing process, it is true that

$$p(H = H^0) \triangleq p_0 = 0.2 \quad (2.25)$$

$$p(H = H^1) \triangleq p_1 = 0.8 \quad (2.26)$$

Furthermore, the essential feature of the diffraction image obtained on each test is the general orientation of the image. Let y_i represent the observed orientation and assume that a reasonable characterization of the likely orientation y_i , given H , is that of a normal distribution:

$$p(y_i | H^k) \sim N(\rho_k, \sigma_i^2) \quad k = 0,1 \quad i = 1,2 \quad (2.27)$$

(It is assumed that $\sigma_i \ll 180^\circ$, so that the mod 2π periodicity of ρ may be neglected.) The variances in observed orientation reflect the effects of impurities in material, positioning errors in conducting the tests, and other variations that are intrinsic to the test itself. It is assumed, however, that the observed diffraction orientations (values of y_i) are independent of each other, given the value of H . Finally, the indication sent by the first test station to the second is limited to a binary 0 or 1

message. Similarly, the determination at the second station is an either/or decision; v can be either 0 or 1.

An analytic organization structure for the inspection task has now been defined, and it happens that it falls within the class of distributed detection networks as described in the previous section. Two tandem operators have been used to form the organization, with the overall task being to judge, or detect, whether the crystalline structure is of type 0 or type 1. However, because the inspection organization makes repeated judgements, a slight generalization of the static DDN structure is required. It will be assumed that each wafer has taken on its crystalline structure independently of all other wafers. Analytically, this means that the value of H for each wafer is independent of that of all others. In effect, then, the inspection organization is executing a detection task repeatedly, but independently of all other wafer inspections made.

Within the analytic structure defined and in view of the operating environment of the inspection organization, several generalized parameters can be specified as part of ω_i . First, the a priori likelihood of crystalline structure type is subject to variation. Second, there is uncertainty in the conveyor belt speed. Both of these parameters influence the environment of both members. Hence ω_1 and ω_2 are taken to be identical:

$$\omega_1 = \omega_2 = (R, p(H)) \quad (2.28)$$

In addition, nominal values can be assigned to ω_i based on the design problem statement.

2.4.3 Inspection Decision Rules - Step C

The organization structure specified for the inspection task requires one human at each test station to judge diffraction patterns. Within the analytic structure, this processing is represented by a mapping γ_i , where

in particular

$$\gamma_1 \in \Gamma_1 = \{\gamma_1 | Y_1 \rightarrow p(u)\} \quad (2.29)$$

$$\gamma_2 \in \Gamma_2 = \{\gamma_2 | Y_2 \times U \rightarrow p(v)\} \quad (2.30)$$

To determine the optimal mappings for the organization, a performance criterion is needed that reflects design goals. From the design problem statement in Step A, it is of interest to minimize the inspection error probability in the organization. This is the performance criterion that will be adopted for the organization. That is,

$$J_0 = p(v=0, H=H^1) + p(v=1, H=H^0) \quad (2.31)$$

From the definition of organization structure, it is evident that J_0 depends on the input/output mappings selected. Furthermore, it is straightforward to show the dependence of J_0 on ω through $p(H)$. At this point in the design, however, the conveyor belt speed R does not affect organization performance. Essentially, whatever input/output mapping is specified is assumed to be executed instantaneously. This is one reason why decision rules represent ideal human behavior only, and not necessarily actual behavior.

Given that the analytic organization structure is of the DDN type, determination of the decision rules for each test station can proceed using the technique described earlier. Figure 2.5 shows the organization

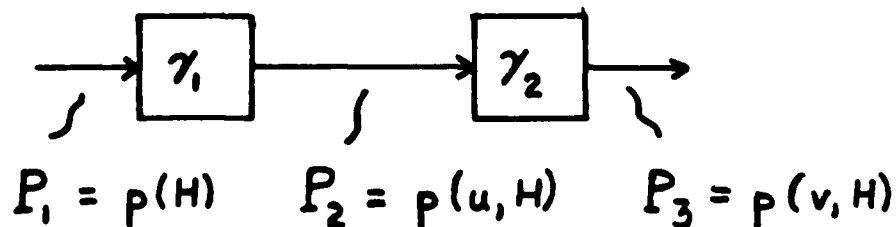


Figure 2.5 Set-up for Determining Inspection Rules

structure labelled according to the sweep pattern to be used. Three stages are shown, including a terminal stage corresponding to P_1 . Because of the performance measure on the organization, only a terminal cost is present. This satisfies the stagewise separation that is required for the solution technique to proceed.

At stage 3,

$$V_3^*(P_1) = p(v=0, H=H^1) + p(v=1, H=H^0) \quad (2.32)$$

Sweeping backward to the middle stage, the problem

$$V_2^*(P_2) = \min_{\gamma_2} \{ E \{ V_3^*(P_3) \} \} \quad (2.33)$$

must be solved. That is, given a P_2 distribution, the characteristics of y_2 together with the input/output mapping γ_2 determine P_3 . The optimization problem in (2.33) selects the minimizing γ_2 for each possible P_2 . The solution for γ_2^* is known [7] and has the form of a threshold test:

$$\gamma_2^* : \quad \text{if } u = j \text{ and } \begin{cases} y_2 \geq t_{2j}^* & v = 1 \\ y_2 < t_{2j}^* & v = 0 \end{cases} \quad j = 0, 1 \quad (2.34)$$

Values of the thresholds t_{2j}^* are dependent on the distribution P_2 . Let p_{jk} denote $p(u=j, H=H^k)$. Then

$$t_{20}^* = \frac{2(\sigma_2)^2 \log(p_{01}/p_{00}) + (\rho_0)^2 - (\rho_1)^2}{2(\rho_0 - \rho_1)} \quad (2.35)$$

$$t_{21}^* = \frac{2(\sigma_2)^2 \log(p_{11}/p_{10}) + (\rho_0)^2 - (\rho_1)^2}{2(\rho_0 - \rho_1)} \quad (2.36)$$

Continuing backward to the first stage, the decision rule at the first test station is determined as the solution to

$$V_1^*(P_1) = \min_{\gamma_1} \{E\{V_2^*(P_2)\}\} \quad (2.37)$$

Again, for a given P_1 , the distribution on y_1 and the input/output mapping γ_1 determine P_2 . Thus the minimizing γ_1 can be found as a function of P_1 . The form of γ_1^* is also that of a threshold test

$$\gamma_1^* : \begin{cases} \text{if } y_1 \geq t_1^* & u = 1 \\ \text{else} & u = 0 \end{cases} \quad (2.38)$$

The value of t_1^* depends of P_1 . Since P_1 is known (or least fixed at its nominal value), t_1^* is thereby chosen. This in turn determines P_2^* and thereby selects $t_{2,j}^*$, which finally determines P_3^* . From P_3^* the value of $J_0(\gamma^*, \omega^N)$ is known, which is the minimum inspection error probability possible using the current organization structure.

In sum the operation of the analytic organization structure using its decision rules is as follows. For a given wafer, the orientation of its diffraction pattern in the first test is judged with respect to the angle t_1^* . If it is greater than t_1^* , a message is sent to suggest that the crystalline structure is usable (i.e. $u = 1$). At the second test station this message is used to select the angle threshold against which to judge the orientation of the second test's observed diffraction pattern. If the perceived angle is less than the threshold, then the wafer is discarded as unusable. Since $t_{2,0}^* > t_{2,1}^*$, the result of the first test is to bias the outcome of the second test.

A final step remains to complete Phase I of the methodology: the assessment of whether the basic organization structure as proposed is likely to be adequate for the task.

2.4.4 Evaluation of Analytic Structure - Step D

A working analytic organization structure has now been constructed to

accomplish the component inspection task. Before expending effort to implement the decision rule for each organization member, however, it is useful to consider whether the structure itself, given idealized behavior, meets design goals. If not, there is little chance that the implementation will meet design goals, since actual behavior can be no better than idealized behavior. In the present situation, the first evaluation criterion is whether the probability of error in detecting defective components is within the specified design limits. In other words, is

$$J_0(\gamma^*, \omega^N) \leq \bar{J}_0 ? \quad (2.39)$$

Assuming eq.(2.39) is satisfied, further evaluation of the structure might include investigation of the sensitivity of $J_0(\gamma^*, \omega^N)$ to changes in the value of ω , which in the present situation would only involve changes in $p(H)$ since R is not part of the analytic structure.

If evaluation of the structure points up a weakness, a revision may be in order. Specific changes to be made would depend on the particular weakness discovered. One possible revision would be to incorporate more diffraction tests into the structure, possibly in the form of additional tandem operators in the network. If, however, the analytic organization structure satisfies the various evaluation criteria posed as part of Step D, then Phase I of the design process is complete and attention can be focused on realizing the decision rules as actual human information processing tasks.

III. IMPLEMENTATION OF DECISION RULES - PHASE II

After a job description for each organization member has been obtained in the form of a decision rule, consideration is focused on the implementation of these rules. This is Phase II of the design process and corresponds to Steps E and F of the methodology. Basically, Phase II is concerned with (a) the translation of a mathematical statement of a desired relationship from inputs to outputs into a physical set-up in which humans can attempt to realize this desired relationship (Step E); and (b) the development of a description of the actual input/output relationship realized using the chosen physical set-up, along with a description of the induced workload (Step F). In (b), the former is the member's task situation and the latter is the information processing model of the task.

In the sections that follow, Phase II methodology steps are first discussed in general terms. The second section relates Phase II considerations to other work. A third section delineates a particular class of information processing models and discusses the execution of Phase II in terms of this class. Finally, execution of Steps E and F is considered for one of the members in the analytic organization structure that was suggested in Chapter 2 for the inspection task.

3.1 Phase II Methodology Steps

3.1.1 Devising a Task Situation - Step E

In Step E of the methodology, a physical set-up is devised so that the information processing that a decision rule represents can, to the greatest extent possible, be realized by humans. Such a set-up, or task situation, includes all physical aspects of the means whereby inputs x_i and y_i are presented to an organization member. It also includes the physical means whereby values from the sets U_i and V_i can be selected as

responses by the member. Besides the physical mechanisms that are directly involved with input and output variables, task situation specification takes into consideration, as necessary, the immediate surroundings in which the human is to be placed when executing the task. Space limitations and ambient noise, for example, are factors that could influence the specification of the task situation.

Because of the several human sensory modes and the variety of possibilities for presenting information using the modes, the designer has many options when devising a task situation. Inputs might be presented visually or by using auditory cues. Similarly, output responses might be registered using voice or manual mechanisms. The selection from among the many options is left largely to the judgement of the designer; in making these choices, however, the designer should take into consideration human factors. Indeed, Step E represents the primary opportunity to do so in the design process.

In approaching the determination of a task situation and weighing the alternatives, the designer should use the decision rule γ_i^* as a guide. The aim should be to specify, with due regard for the member's immediate surroundings, a collection of equipment, and directions for how it is to be used, so that it is possible for the member to execute, at least to some approximation, the decision rule for the task. Whether or not the member will actually achieve γ_i^* is considered in subsequent design steps. To the extent that the designer can anticipate at this point the processing load that a given task situation will induce, so much the better, since this may aid subsequent design considerations. However, the focus in Step E is on translating key structural characteristics of the decision rule into a physical form.

Suppose now that a given member's task situation has been put into place. That is, the collection of hardware chosen to implement the decision rule has been installed and the member has been trained to use it. The next design step will be to represent the human information processing behavior at this task. This behavior will in general be tied

to the characteristics of the task situation. However, task situation equipment, once installed, may have a number of features that can be adjusted. For example, if a visual display is part of the set-up, its intensity is something that can be adjusted. On a different level, elements of the display itself might be available for adjustment, such as the position and/or presence of a coordinate grid that is superimposed on a display of terrain features. Variation in task situation characteristics will also affect human behavior at task execution. Therefore, in anticipation of subsequent design steps, completion of Step E requires the delineation of a set of variables that are available for adjustment within the task situation, and which are expected to impact the information processing behavior of the member as he performs his task. These variables are the task situation parameters, and are designated by θ_i .

When the design is completed for an organization task, the parameters θ_i will be fixed, i.e. hard-wired, at selected values. Because of their potential effect on human information processing behavior, however, it is not known at this point in the design what setting for θ_i will be most advantageous from the organization's point of view. Thus θ_i is left as a free variable within the task situation structure for the time being. As with the overall task situation, to the extent that the designer can anticipate what effect certain parameters will have on later information processing behavior, it may be possible to confine θ_i to a small number of parameters that have a significant effect on the organization, rather than having a larger number, many of which do not substantially affect information processing behavior.

3.1.2 Developing an Information Processing Model - Step F

Though a task situation has been devised with ideal organization member behavior in mind, it will be unlikely that actual human behavior will match exactly that which is desired. This may be due to human limitations and/or to compromises made in developing the task situation.

What is needed, therefore, is a description of how an organization member actually accomplishes the information processing that his task situation requires. This is the purpose of Step F in the methodology. There are two elements of the description. One is a characterization of the actual input/output processing behavior and the other is a measure of the workload induced by the task. Together, they constitute the information processing model of the task.

Given that the task situation provides a means for the organization member to select responses u_i and v_i based on inputs z_i and y_i , the input/output behavior realized will by definition be a mapping from the set Γ_i . Denote this mapping by k_i to distinguish it from other elements of Γ_i , particularly γ_i^* . In the sequel it will be convenient to view k_i in terms of a conditional probability distribution. Denote by \bar{k}_i the distribution $p(u_i, v_i | z_i, y_i)$ that is associated with the mapping k_i .

The second element of an information processing model is a description of the workload induced by the task, which itself has two aspects. The first is the definition of a workload measure that is appropriate to the task. Besides the measure, however, it is necessary to specify, in like terms, at what point human limitations become a factor, i.e. at what point the human is overloaded. For example, if workload is measured in terms of tasks executed per hour, then the overload point would be represented as some maximum number of task executions per hour. Let w_i and \bar{w}_i denote the workload measure and limit, respectively. Note that, depending on the behavior that results and its consequences for the organization, operation in a overloaded state (where $w_i > \bar{w}_i$) may not be undesirable. To make such a judgement, however, it is necessary to have an input/output description that is valid for operation in the region of overload.

For some tasks, it may be appropriate to use a multi-dimensional workload measure. Because workload dimensions may not be independent, a generalization is required to specify workload limits in this case. While this is possible in the present context, it needlessly complicates

discussion of the methodology. Therefore, a single-dimensional measure will be assumed.

Both elements of the information processing model will in general be affected by the characteristics of the organization member's surroundings. In terms of the current framework, this means that k_i and w_i will depend on ω_i , π_i and θ_i . The generalized parameters ω_i have already been included in the formulation of a performance criterion. Here their effect, particularly on workload, might be through the statistical characteristics of y_i . Similarly, the statistical characteristics of z_i may affect workload. This latter possibility is captured through the generalized parameters π_i . Finally, as discussed in connection with Step E, task situation parameters have been defined primarily because their values are expected to influence the information processing model.

In addition to characteristics that are external to the human, information processing behavior may also depend on choices made that are internal to the human. This may be the case if, by training or by design, the human has developed or been provided with more than one option for accomplishing the information processing required of him. For example, suppose that the human is to perform some type of inspection task and that two methods are available to him for this purpose. One method involves a detailed examination process, but the other is such that only a cursory examination is made. Depending on how the human chooses between his two methods, processing load and processing performance at the inspection task will vary. To account for the possibility that options in information processing may be available, a set of variables that represents the selection of options is postulated as part of the information processing model structure. These variables are called information processing parameters and are denoted by λ_i .

As with task situation parameters, the values of λ_i are not assigned at this point in the design, but rather remain as free variables whose values are to be selected later in the design process. Unlike values of θ_i , however, it is not necessarily possible to "hard-wire" λ_i values.

Instead, one of two interpretations can be assigned to selected λ_i values. The first is that they represent predictions for how an organization member will elect to exercise his options. The second is that they designate how the member should be trained to exercise his options. Either may be appropriate, depending on the particular circumstances.

The different λ_i interpretations point out that human information processing behavior in the organization can also be viewed as a matter for design. If the designer can specify the task situation, then he can also specify to some extent how the organization member should operate within that situation, instead of leaving the member to infer and develop his own method of operation. Thus specific training at a task in order to realize desired input/output behavior is well within the limits of the design process, and can be used to arrive at an information processing model of choice, rather than one governed by circumstances.

At the completion of Step F, an information processing model, with input/output and workload components, will exist for each member that incorporates the effects of external and internal parameters. Formally, the quantities

$$k_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad (3.1)$$

$$w_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad (3.2)$$

$$\bar{w}_i \quad (3.3)$$

will be specified for organization members. The form in (3.1) is used to represent the fact that the realized input/output mapping k_i changes as the values of θ_i , λ_i , ω_i , and π_i change.

At this point in the design process, the organization structure is essentially complete. In addition to the analytic organization structure, the task situation has provided members with the physical structure to do their respective tasks and the information processing model has structured the members' processing behavior. It remains to select values of parameters within the structure, which is the issue taken up in Phase III of the design.

3.2 Approaches to Phase II Execution

The specification of (a) a working environment, (b) a particular task to be performed by humans within that environment and (c) a measure of workload for that task has been the subject of much scientific investigation. This section discusses some of the approaches and methods that have been developed as a result of these investigations, particularly those that appear to be of direct use in executing Phase II of the methodology.

The discussion is organized into two parts as follows. First, resources in the literature are cited from which approaches can be extracted for decision rule implementation. A separation is made between the physical characteristics of an implementation (task situation) and the mental characteristics (information processing model). In practice this distinction is not so clear. For example, it may be of considerable advantage to specify a task situation for which the information processing requirements are well-understood, and thus simplify execution of Step F. Motivated by this interrelatedness, the second part of the discussion suggests a particular viewpoint for applying the approaches cited to the execution of Phase II.

3.2.1 Approaches to Decision Rule Implementation

Physical Characteristics: Task Situation

As outlined in 3.1, one aspect of decision rule implementation is the specification of the physical features of the organization member's task, such as displays and mechanisms for response to inputs. Issues that are considered in this regard might include positioning of task situation elements, both with respect to each other and to the organization member, color and intensity of a display, or the coding and presentation of input

information. All of these considerations fall within the realm of human factors engineering, for which there exists a substantial literature. Several recent texts [15], [16], [17] present an orderly treatment of issues that can arise in task situation development.

Mental Characteristics: Information Processing Model

The two elements of an information processing model are a description of the input/output processing behavior of the organization member, and a description of processing load that the task induces. In principle one could approach the development of these elements independently. A description of the input/output processing could be obtained, for example, by constructing a simple table based on observation of the organization member as he performs the task. However, input/output processing activity is usually highly correlated with processing load, and thus the two elements should not be separated. A majority of the approaches that might be used to develop an information processing model pursue a description of both elements of the model simultaneously with the goal understanding how one interacts with the other. This is often done by identifying variables that have an effect on both performance of the task and task workload. In the present context, such variables correspond to the task situation parameters (θ_i) and the choices in processing (λ_i) described earlier.

There exist many approaches to measuring human workload in routine information processing tasks, motivated by a variety of issues and involving a number of scientific disciplines. A recent classification by Sanders [18] defines three broad categories of workload models: (1) psychophysiological measures, (2) subjective measures and (3) behavioral measures. In the first, measurements of physiological quantities, such as heartbeat rate, are correlated with changes in task conditions. A task condition that produces a higher heartbeat rate, for example, is considered to have a higher workload. The second category uses subjective assessment techniques to arrive at an ordering of the workload induced by a particular set of task conditions. For example, a subjective scale is often used to rate the flyability of an airplane, with the implication

that an improvement in flyability rating corresponds to a lower workload. Soulsby [19] surveys the literature on these two approaches to workload modeling. Moray [20] also discusses physiological approaches to describing workload.

While the use of psychophysiological and subjective measures are viable approaches to workload characterization, the third category is perhaps the most directly applicable in the present context. This category includes the so-called class of "spare capacity" approaches, where a secondary task is used as a device to arrive at a measure of workload for the primary task. Also included in the category of behavioral measures is an approach that models workload directly using mathematical equations. Information theoretic models and the optimal control model are examples of this approach. Soulsby [19] also surveys the literature pertaining to this class of approaches, and Moray [20] includes relevant discussion that is organized into control engineering, experimental psychology and mathematical modeling sections. In addition, Pew, et al. [21] present an extensive review of mathematical models of human performance at information processing tasks. In more specific work, Rouse [22] develops mathematical models for estimation tasks, and Green and Swets [23] present a detailed treatment of the application of signal detection theory to human performance for detection tasks.

In addition to approaches that aim to model and assess workload, Phase II of the methodology can be informed by results from valid simulation models of human behavior. PROCURU [24] and the Human Operator Simulator HOS [25] are among the models of this type. Finally, there exists an extensive literature in experimental psychology and mathematical psychology that documents and predicts human behavior in various situations and under various conditions. Though the emphasis in these disciplines is on understanding human characteristics on a much more fundamental level, execution of Phase II can still benefit from the knowledge available.

3.2.2 A View on Applying Approaches to Decision Rule Implementation

Many of the approaches cited above, particularly those that seek to represent human behavior using mathematical models, begin with a particular task or class of tasks (e.g signal detection or manual control) for which it is desired to assess and/or predict human performance and workload. A model is then built that reflects fundamental aspects of the task, and is tested for its validity with respect to some explanatory or predictive expectations. This type of approach thus proceeds from (1) a specific task to (2) a model of human execution of the task, and then to (3) an evaluation of the model's validity. This process is illustrated in part (a) of Figure 3.1. Often the mathematical model is normative, i.e.

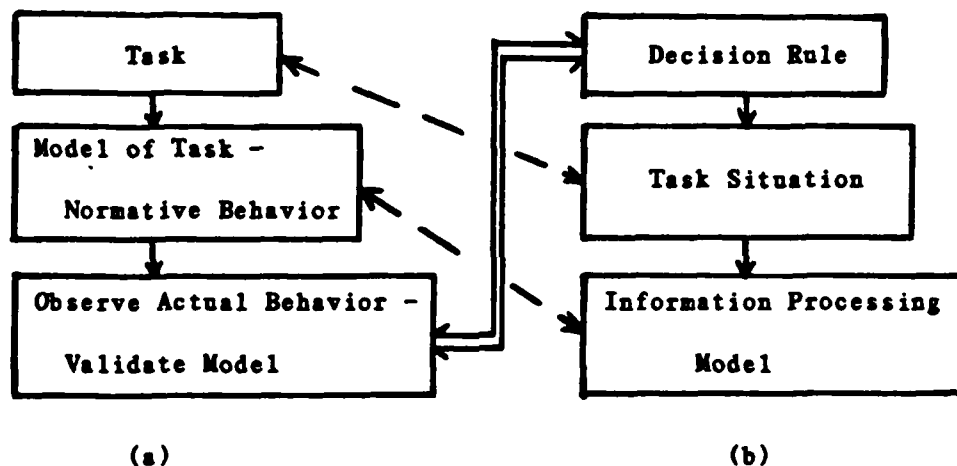


Figure 3.1 Comparison of Approaches (a) Human Modeling (b) Phase II of Methodology

ideal human behavior within the task is prescribed. Observed behavior is then used to assess whether human performance matches normative expectations.

In the context of organization design, steps similar to those outlined above are taken in the course of completing Phase II of the methodology. A key difference exists, however, in the order that they occur. Instead of beginning with a specific task to model, Phase II begins with a statement of normative behavior in the form of a decision

rule. In subsequent steps a task situation and an information processing model are developed that realize as closely as possible normative behavior. In executing these steps, it would be of great benefit to have some basis for deciding what kind of task situation to specify in an attempt to implement a given decision rule. Such a basis exists, however, in the form of validated models that have been developed using the approach of Figure 3.1a. Thus, given a particular decision rule, the designer can undertake a matching process (double arrow in Figure 3.1) whereby he seeks to find an already documented description of human behavior that is similar to the processing that is to be realized. If a match can be found that is satisfactory, the task for which the matching description was developed can become the task situation for the organization member, and the mathematical model of the task can become a central part of the organization member's information processing model.

Conceptually, then, the organization designer can view much of the work in human modeling as being a catalog, with each item listed according to a description of input/output processing accomplished. Under each entry is a description of the task from which and for which the processing model was developed, along with the workload model for that task. Given a specific decision rule to implement, the designer can then look through the catalog for an entry or entries that meet his needs. Having a decision rule to match enables the designer to focus his efforts. This focus is viewed as a key advantage of the methodology.

3.3 A Class of Information Processing Models

As a vehicle for illustrating more concretely the various aspects of an information processing model, this section describes a particular class of such models and discusses Step F in terms of this class. Definition of the class is based on assumptions commonly used by investigators to model human information processing, and in some sense represents only a restatement of these assumptions in terms of the present framework. It should be emphasized that while the discussion in this section is intended

to be illustrative, the class of models considered does not exhaust the information processing models that are possible outcomes of Step F.

The following paragraphs first consider the basic building block of the class, which is a procedure. Subsequent discussion considers how procedures are combined to form more complex models and indicates how the quantities θ , ω , λ , and π might be manifested in terms of this class.

3.3.1 Procedures

Sanders [18] identifies a number of viewpoints that have been taken when modeling human behavior, including the view of humans as limited capacity processors. A fundamental premise in several approaches based on this view is that humans accomplish information processing tasks using "programmes". A program is a sequence of mental processing steps that are executed as a unit. Such a view is particularly appropriate in connection with a routine task at which the human has had much practice. Completing the task is simply a matter of exercising the program that the human has developed for that task.

Another premise that is (according to Sanders) often associated with a limited capacity model is that mental processing resources are allocated in an all or nothing fashion to complete a task. As a consequence, processing load is directly related to observed processing time. Tasks that require more time to complete have required more processing resources and hence have a higher workload.

These two premises can be formalized in the present context as follows. Given that a mental processing program, or procedure, exists and is being used to accomplish a task, there emerges a well-defined relationship between inputs and outputs that characterizes the procedure. Indeed, in some sense it gives the procedure its identity. In terms of Step F considerations, this relationship qualifies as an input/output description. Denote by k_p the input/output mapping associated with a

procedure. Finally, if procedure execution time is taken to be in direct proportion to the use of mental processing resources, it is possible to derive a measure on task workload using processing time.

3.3.2 Information Processing Models Using Procedures

Single Procedure

Using the concept of a procedure, the construction of an information processing model can be considered in more specific terms. In the simplest case, suppose that member i 's task situation is such that a single procedure is executed to accomplish the required information processing. The input/output behavior for the task is the input/output behavior that procedure execution determines:

$$k_i \leftrightarrow k_p \quad (3.4)$$

Now assume, for purposes of argument, that inputs y arrive from the environment once every τ time units and that a response u is required for each one. Thus the procedure must be executed every τ time units. However, procedure execution time is a variable quantity. It depends in general on the current values of input variables z and y . It also depends on the characteristics of the task situation. In particular, processing time will vary as task situation parameters are varied. Finally, in addition to the time required specifically for procedure execution, overall observed processing time will include a component due to human sensory-motor delays. There will be associated with this component a certain variability as well.

In view of the above, a workload measure for the procedure is suggested as follows. Given the conditions affecting procedure execution time, the overall processing time for a single procedure execution might be represented as a random variable t_p drawn from a distribution $h_p(\theta_i, z_i, y_i)$, where the distribution itself characterizes sensory-motor

variation. Assuming h_p to be independent of input characteristics, then the average processing time, as a function of θ_i , is given formally as a conditional expectation:

$$\bar{t}_p(\theta_i) = E(t_p | \theta_i) = \int_{z_i} \int_{y_i} \int_{t_p} h_p(\theta_i, z_i, y_i) p(z_i | y_i) p(y_i) dt_p dy_i dz_i \quad (3.5)$$

To arrive at a workload measure, it is necessary to incorporate eq.(3.5) with the requirement that one procedure execution be completed every τ time units. This can be done by forming the ratio of the two quantities. That is, define

$$w_i = \frac{\bar{t}_p(\theta_i)}{\tau} \quad (3.6)$$

If the average procedure execution time exceeds the interarrival time, then the organization member will be unable to complete procedure executions fast enough; he will be overloaded. Conversely, if \bar{t}_p is less than τ , there is sufficient time for the member to use his procedure. Thus the processing load limit is reached when w_i is unity, i.e.

$$\bar{w}_i = 1 \quad (3.7)$$

From eq.(3.5) and eq.(3.6), it is evident how workload depends on factors external to the organization member. In particular, the generalized parameters ω_i and π_i are given as

$$\omega_i = (p(y_i), \tau) \quad (3.8)$$

$$\pi_i = (p(z_i | y_i)) \quad (3.9)$$

In eq.(3.5), the dependence of task situation parameters has also been included explicitly. Moreover, in addition to affecting processing time, it is possible that θ_i will have an impact on the procedure's input/output characteristics. This would be the case, say, if one of the steps within the procedure was accomplished directly in terms of a task situation parameter.

Multiple Procedure Tasks

The discussion above has been for the relatively simple case where a single procedure is used to accomplish a given task. Now consider the case where an organization member possesses more than one procedure. This might occur, for example, if he has been trained to perform a task more than one way. It might also occur as a consequence of a decision rule's form. That is, the task itself may be such that it decomposes into two distinct information processing tasks, each of which has a procedure associated with it.

In instances where the organization member has more than one procedure, a selection is required as to which procedure is to be used at a given time. In general, this selection will be made based on the current inputs and also according to the member's preferences. The latter dependency is an example of a choice made internally by the member.

The notion of a multi-procedure information processing model can be formalized as follows. Denote by $p_i(j|z_i, y_i)$ the probability that the j^{th} procedure of member i will be used, given that the inputs z_i and y_i are to be processed. The overall input/output conditional distribution \bar{k}_i is then

$$\bar{k}_i = \sum_j p_i(j|z_i, y_i) \cdot \bar{k}_{pij} \quad (3.10)$$

The distribution $p_i(j|z_i, y_i)$ represents a selection among processing options and \bar{k}_{pij} designates the j^{th} procedure of the i^{th} member.

To the extent that procedure selection is made at the member's discretion, $p_i(j|z_i, y_i)$ designates a choice internal to the human. Thus the information processing parameters will in general include some subset of the possible distributions $p_i(j|z_i, y_i)$. In an extreme case where procedure selection is entirely up to the member, λ_i contains $p_i(j|z_i, y_i)$

as a free parameter, i.e.

$$\lambda_i = (p_i(j|z_i, y_i)) \quad (3.11)$$

where

$$\sum_j p_i(j|z_i, y_i) = 1, \quad p_i(j|z_i, y_i) \geq 0 \quad (3.12)$$

The workload measure for a multi-procedure model has a form similar to that of eq.(3.10). By including the conditional distribution for procedure selection in eq.(3.5), the overall average processing time T_{pi} is expressed as

$$T_{pi} = \sum_j [p_i(j) \cdot \bar{t}_{pij}(\theta_i)] \quad (3.13)$$

Assuming the processing rate requirements are as discussed earlier, substituting $T_{pi}(\theta_i)$ for the numerator in eq.(3.6) yields a workload measure that reflects the multi-procedure situation. Eq.(3.13) may not be a complete characterization of processing time in some situations, however. Sanders [18] notes that additional processing resources and hence additional processing time may be required to switch procedures. This has been observed and modeled in [26] using an approach based on procedures. In particular, processing time for switching was found to depend on the relative frequency of switching to a given procedure. Thus a more accurate model might include an extra term (\bar{t}_{sij}) for the average procedure switching time:

$$T_{pi} = \sum_j [p_i(j) \cdot \bar{t}_{pij}(\theta_i) + \bar{t}_{sij}(p_i(j))] \quad (3.14)$$

3.3.3 Summary

This section has considered information processing models in more specific terms. In particular, a procedure was defined as a model form that is appropriate for characterizing information processing in routine tasks. Using procedures as a basis for discussion, it was indicated how each of the quantities used as arguments in the general information processing model formalism might be realized in practice. These quantities include task situation parameters θ_i , information processing parameters λ_i , interactions with other members π_i , and generalized parameters that derive from interaction with the member's environment ω_i . It should be emphasized that the discussion has been primarily for illustration and the model is not intended as the necessary basis for all information processing models. The form will find use elsewhere in the thesis, however, including the next section where an information processing model is suggested for the first member in the inspection organization that was considered in Chapter 2.

3.4 Execution of Phase II - Example

To further illustrate Phase II of the design process, this section discusses the execution of Steps E and F for a specific decision rule.

Job Description

Recall the inspection task described in Chapter 2. A two member analytic organization structure was proposed, where each member was to perform a test on wafers of crystalline material as they passed by on a conveying system. Both tests were such that the diffraction angle from an irradiated component was used as an indication of its crystalline structure. The tests were not perfect, however, and decision rules were established for each organization member. For the first member, this rule was a single threshold test:

$$y_1^* : \begin{cases} \text{if } y_1 > t_1^* & \text{say } u = 1 \\ \text{else} & \text{say } u = 0 \end{cases} \quad (3.15)$$

Eq.(3.15) represents ideal behavior by the first organization member. As such, it serves as a target for the specification of a scheme whereby a human can actually observe the diffraction pattern and register his judgement as a response.

3.4.1 Task Situation - Step E

The basic characteristics of the test procedure are a brief illumination of the wafer and the ability to observe the diffraction pattern that is returned from the wafer. This immediately suggests the form of the task situation required: it must be such that a visual display of the pattern is presented to the member. Furthermore, since by design the organization member is to select one of two responses based on the observed pattern, two mechanical buttons can be provided for this purpose.

To complete the task situation structure, it is necessary to adapt the test to the fact that the wafers are moving, and also to find a means whereby the threshold t_1 can be used in judging crystalline structure type. To resolve the first issue, it is reasonable to assume that the illumination and return of a diffraction pattern can take place quickly with respect to a moving wafer's speed and that the diffraction image can be stored. Equipment that accomplishes this can be built into the task situation.

To resolve the second issue, the threshold angle for discriminating between crystalline types can be superimposed on the displayed diffraction image. Thus the organization member's task situation can be represented as shown in Figure 3.2. The threshold angle for comparison has been depicted as a double-headed arrow, and a representative diffraction image

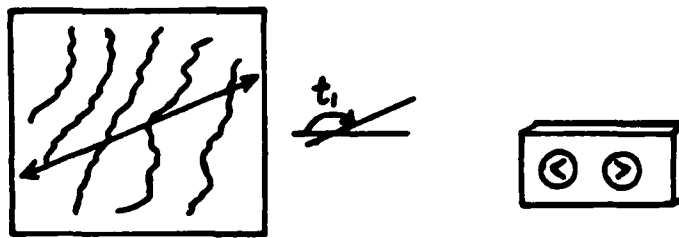


Image Display

Response Mechanism

Figure 3.2 Task Situation for First Organization Member

has been shown. The processing task of the organization member is to judge whether, on the whole, the pattern is oriented at an angle greater than or less than the threshold angle. Depending on the judgement made, either the "<" or ">" button is pressed, which corresponds to $u = 0$ or 1, respectively. Completion of the processing occurs when a button is depressed, the response made is then forwarded to the second member. The image also clears and the diffraction image for the next wafer is displayed when it becomes available.

Thus the task situation consists of a mechanism for obtaining diffraction images, and for displaying them with the threshold t_1 superimposed. It also includes the mechanical buttons that register the member's response. Since these two elements together act to present the observation y_1 and to provide a means for selecting a response u , the task situation is one that meets the basic requirements of the decision rule. Other elements of the task situation are the physical position of the display equipment with respect to the conveyor, as well as the position of the human with respect to the display and response buttons. Together they make up the structure of the task situation.

From Figure 3.2, it is apparent that the orientation of the double-headed arrow will affect the responses made by the organization member, and will thereby impact the realized input/output processing behavior. It also happens that the value of t_1 will affect workload, as will be

discussed shortly. Therefore, t_1 is selected as a task situation parameter. Although there are probably several other parameters that could be identified that affect the member's diffraction image processing behavior, such as display intensity or display resolution, only one will be included here as part of θ_1 :

$$\theta_1 = (t_1) \quad (3.16)$$

3.4.2 Information Processing Model - Step F

Given the task situation for accomplishing the diffraction image test, a description of human behavior at the task is now needed. It will be assumed that the task situation represents a routine information processing task, and that with practice the member will develop a mental processing program for doing the task. Thus a single procedure model is postulated. While data has not been gathered to substantiate and validate the model suggested, the task itself is similar to one for which data has been collected (see chapter five). With this caveat, the information processing model for the first member in the inspection organization is as follows.

Once the member becomes comfortable with his task, there will emerge a well-defined input/output behavior that characterizes the mental procedure that is being executed. Because of the borderline cases in judging diffraction patterns, the comparison with t_1 will not be perfectly deterministic, however. Instead, actual human behavior will correspond to a conditional distribution \bar{k}_{11} (which implies an input/output mapping k_{11}) of the form

$$\bar{k}_{11} \leftrightarrow p(u|y_1) \quad (3.17)$$

where

$$p(u|y_1) : \begin{cases} \text{if } y_1 \geq t_1 & u = 1 \text{ wp } 1-\beta \\ & u = 0 \text{ wp } \beta \\ \text{if } y_1 < t_1 & u = 1 \text{ wp } \beta \\ & u = 0 \text{ wp } 1-\beta \end{cases} \quad (3.18)$$

As before, the double subscript ij designates the j^{th} procedure of member i . (The notation k_{11} has been used in anticipation of further discussion in chapter four.) According to eq.(3.18), the organization member makes an error with probability of β in judging y_1 with respect to t_1 . If β is small, the realized behavior is close to the ideal behavior sought, and the decision rule has been implemented reasonably well. As β becomes larger, the success of the implementation comes into question. A reworking of the task situation may be warranted, or perhaps better training of the organization member at the task is needed. The necessity to do so is not clear at this point, however, since the implementation can best be assessed only in view of the overall organization. Finally, note that the task situation parameter t_1 directly influences the characteristics of k_{11} .

Following the discussion in section 3.3 regarding procedures, mental processing resources and processing time, the measure of workload for the member will be derived using observed procedure execution time. In particular, assume that average procedure execution time, denoted \bar{t}_{p11} , depends only on t_1 . As t_1 ranges from 0 to 180, the variation in \bar{t}_{p11} is shown in Figure 3.3. The underlying effect is that as the threshold

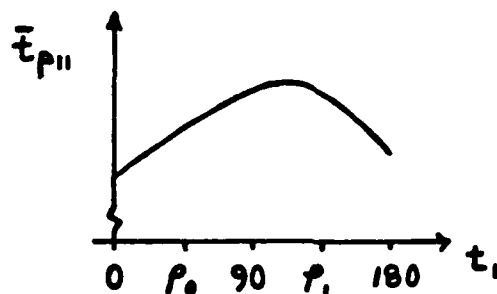


Figure 3.3 Average Time For Procedure Execution

comparison rule moves closer to the horizontal, it becomes less uncertain

a priori as to what response will be selected. The asymmetry about $t_1 = 90$ is because of the distribution on observations. Response time is highest when diffraction images are equally likely to be oriented on either side of the threshold. Since there is an unequal distribution on crystalline structure types, the value of t_1 that makes u equally likely to be 0 or 1 is closer to the more likely value of p_i , which is p_1 . Although changes in $p(H)$ will in general affect \bar{t}_{p11} , it is assumed that the characteristic shown in Figure 3.3 will remain valid as $p(H)$ takes on values within the range specified in the design problem statement.

Combining the average processing time measure with the requirement that patterns must be processed fast enough to keep up with the conveyor speed, the workload measure of the first member is given as

$$w_1 = \bar{t}_{p11}(t_1) \cdot R \quad (3.19)$$

with a processing load limit of

$$\bar{w}_1 = 1 \quad (3.20)$$

This completes the execution of Step F for the first organization member in the inspection organization. In sum, the information processing model for the task is given as

$$k_1 \leftrightarrow k_{11}(t_1) \quad (3.21)$$

$$w_1 = \bar{t}_{p11}(t_1) \cdot R \quad (3.22)$$

$$\bar{w}_1 = 1 \quad (3.23)$$

The model has explicit dependencies on the task situation parameter (t_1) and on one of the generalized environment parameters (R). There are no internal choices made by the member; hence λ_1 is not a factor. Similarly, the first member does not receive inputs from the second; hence π_1 is also non-existent. Finally, an important point to note is that eq.(3.21) is valid only so long as w_1 does not exceed \bar{w}_1 . That is, the input/output processing behavior represented by k_{11} is a valid description of actual behavior only when the member is not overloaded.

IV. DETERMINATION OF SATISFACTORY NOMINAL DESIGN - PHASE III

Phases I and II of the design process have focused on different, though related, parts of the design. To integrate the design elements obtained in these two phases, a third phase is necessary. It is in this phase that the designer is first provided with an opportunity to view and evaluate the organization design as a whole. It is also during this phase that potential tradeoffs between organization performance and individual member workload are made apparent. Once such tradeoffs have been made and the integration of design elements has been satisfactorily completed, a nominal organization design exists that meets design goals. The design encompasses the specification of basic organization structure, delineation of specific tasks for each organization member, and prescriptions/predictions for how members should/will perform their assigned tasks.

This chapter considers the integration phase of the design methodology, and is organized as follows. In the first section, the specific steps of the methodology that are part of Phase III are discussed in general. These include a step to integrate design elements by placing task situation and information processing parameters for best organization advantage, but also with regard for workload limitations of individual members (Step G). The result of this step is a nominal design. Once a nominal design is obtained, however, it must be evaluated with respect to overall design goals (Step H). Finally, if a nominal design is found to be unsatisfactory, a selection from among various options for modification must be made (Step I).

The second section discusses the execution of Phase II in terms of the inspection organization considered in the previous two chapters. Initially, a nominal design is obtained for this organization that is flawed. Modifications are then made, and eventually a satisfactory nominal design is obtained.

4.1 Phase III Methodology Steps

4.1.1 Obtaining Nominal Design - Step F

Review of Phase I and Phase II Elements

Recall from Chapter 2 that Phase I of the design process has resulted in the specification of an analytic organization structure. This includes the number of organization members, their protocols for interaction, and an analytic objective function J_0 that reflects organization performance goals. This function has been formulated in terms of input/output mappings used by organization members and in terms of the generalized parameters that characterize the interactions of organization members with their respective environments. That is,

$$J_0 = J_0(\gamma, \omega) \quad (4.1)$$

Furthermore, an optimization process in Phase I has selected the optimal input/output mappings, or decision rules γ^* , under the assumption that ω is fixed at its nominal value ω^N , i.e.

$$\gamma^* = \arg \min_{\gamma} J_0(\gamma, \omega^N) \quad (4.2)$$

Phase II has used the decision rule of each member as a normative specification, or job description, of the processing that the member is supposed to perform. A task situation has been constructed so that this processing can take place, and an information processing model has been developed that describes the member's behavior as he performs his task. This description includes an actual input/output characterization (k_i) and a measure of the workload induced by the task (w_i). Both components of the information processing model depend, in general, on task situation (θ_i) and information processing (λ_i) parameters. They also depend on parameters that characterize inter-member interactions (π_i), as well as

parameters that characterize a member's interactions with his environment (ω_i). Written formally, the outcome of Phase II is then given as two expressions:

$$k_i = k_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad (4.3)$$

$$w_i = w_i(\theta_i, \lambda_i, \omega_i, \pi_i) \quad ; \quad \bar{w}_i \quad (4.4)$$

The quantity \bar{w}_i is the workload limit for the organization member and represents the point at which he becomes overloaded.

Integrating Design Elements

In general, the actual input/output relationship realized (eq.(4.3)) by each member does not match that which is desired. Thus the outcome of Phase I does not necessarily merge readily with the outcome of Phase II. The problem of integrating design elements is a non-trivial one, however, since individual workload and input/output relationships both depend on the same set of parameters. On the one hand, it is desirable to adjust each θ_i and λ_i so that input/output relationships k_i are selected that optimize organization performance. However, the possible θ_i , λ_i combinations may be restricted because they induce a workload that exceeds an organization member's limits. In general, then, there will be tradeoffs required between organization performance and individual workload.

The problem of ensuring that Phases I and II converge and of assigning values to θ_i and λ_i can be resolved by substituting k_i for γ_i in J_0 , adding the workload measures of each member as constraints, and minimizing J_0 over possible θ_i , λ_i values. Stated formally, the problem is as follows.

Constrained Nominal Organization Problem (CNO)

$$\min_{\theta, \lambda} J_0(k(\theta, \lambda, \omega^N, \pi), \omega^N)$$

$$\text{s.t. } w_i(\theta_i, \lambda_i, \omega_i^N, \pi_i) \leq \bar{w}_i$$

Note that ω has been fixed at its nominal value ω^N , as it was when originally solving for the decision rules.

For each θ, λ pair a particular set of input/output relationships k is specified. The general goal in Problem CNO is to find the best θ, λ pair with respect to performance that does not violate any individual member's workload constraint. Because of the problem's complexity, however, solution strategies other than finding the global constrained minimum might be pursued. At one extreme is a strategy that seeks to find only feasible values of θ and λ , with a subsequent determination of whether these values are good enough with respect to design goals. Whatever the solution strategy, the outcome of Problem CNO is a set of values for task situation (θ^c) and information processing (λ^c) parameters. (In the sequel, a superscript c will be used to designate solution values and other quantities that are related to Problem CNO.) In addition, a particular set of inter-member interaction characteristics π^c is induced. With $\omega = \omega^N$ and with the given organization structure, θ^c and λ^c complete the specification of a nominal organization design.

As it has been formulated, Problem CNO uses the workload limit as a maximum level constraint on workload. In general, however, this need not be the only form that the workload constraint can take in formulating Problem CNO. While it is true that workload in excess of the workload limit represents a state of overload, it is not necessarily true that the organization member cannot operate in this state. If the input/output model includes a description of behavior when overloaded, then the constraint $w_i \leq \bar{w}_i$ may be included as part of k_i . The essential feature of the problem remains intact, however: workload limitations are taken

into account when optimizing organization performance.

When the nominal design is implemented, each task situation will be hard-wired by setting $\theta_i = \theta_i^c$. However, the values of $\lambda_i = \lambda_i^c$ can be interpreted in either of two ways. One way is to use λ as a prediction of how the organization member will choose to accomplish the information processing within his task. For example, if the member has several options for processing a given input and λ_i models the relative frequency of exercising each option, λ_i^c represents a prediction for how the member will select from among his options. Alternatively, the solution value λ_i^c can be used as an indication of how the organization member should be trained to accomplish his task. Again, for the case where λ_i represents a selection among information processing options, the organization member can be instructed to exercise each of these options with relative frequencies given by λ_i^c .

4.1.2 Evaluating Nominal Design - Step H

Once a solution to Problem CNO has been determined and a nominal design obtained, the designer can consider the organization as a whole and evaluate whether it meets original design goals. This evaluation takes place in Step H of the methodology. A variety of evaluation criteria are possible. One category includes those that relate to the performance of the organization. In particular, if a minimum level of performance, \bar{J}_0 , is required, then the question of whether

$$J_0(k(\theta^c, \lambda^c, \omega^N, \pi^c), \omega^N) \leq \bar{J}_0 \quad (4.5)$$

is of interest. Also of interest in this regard is the sensitivity of organization performance to variation in θ and λ about their selected values:

$$\frac{\partial}{\partial \theta} J_0(k(\theta^c, \lambda^c, \omega^N, \pi^c), \omega^N) ; \quad \frac{\partial}{\partial \lambda} J_0(k(\theta^c, \lambda^c, \omega^N, \pi^c), \omega^N) \quad (4.6)$$

Another evaluation of interest might be to assess the sensitivity of the nominal design to variation in the organization's environmental characteristics, i.e. to variation in ω around ω^N . The quantity

$$\left. \frac{\partial J_0}{\partial \omega} \right|_{\omega^N} \quad (4.7)$$

formally represents this sensitivity. Alternatively, it may be that the environmental interaction characteristics are confined to some specific set $\bar{\Omega}$:

$$\omega \in \bar{\Omega} \quad (4.8)$$

(with $\omega^N \in \bar{\Omega}$ as well). In this situation, it is of interest to evaluate organization performance as ω ranges over values in the set $\bar{\Omega}$ and to determine, for example, whether

$$\max_{\omega \in \bar{\Omega}} \left\{ J_0(k(\theta^c, \lambda^c, \omega, \pi), \omega) \right\} \leq \bar{J}_0 \quad (4.9)$$

In addition to investigating the sensitivity of organization performance with respect to uncertainty in the environment, it is also necessary to assess the sensitivity of individual member workload to such variation. Indeed, this is a key area for evaluation. More generally, it is necessary to ensure that changes in interaction characteristics, either those with other members or those with the environment, do not put the organization member into an operating region that has not been included in the information processing model. For example, if operation in the overload state has not been modeled, then it would be required to ensure that π_i and ω_i do not vary such that

$$w_i(\theta_i^c, \lambda_i^c, \omega_i, \pi_i) > \bar{w}_i \quad (4.10)$$

since if this were to happen the entire organization would be operating in an unknown (or at least unmodeled) region. One strategy for preventing individual member overload is to evaluate w_i over the possible π_i, ω_i pairs and establish that \bar{w}_i is never exceeded. Since π_i is a dependent variable, this evaluation is made with respect to possible ω values:

$$\max_{\omega_i \in \bar{\Omega}_i} \left[w_i(\theta_i^c, \lambda_i^c, \omega_i, \pi_i) \right] \leq \bar{w}_i \quad (4.11)$$

Another alternative for preventing member overload is to ensure that a mechanism exists whereby an organization member can adjust his workload when variations in ω_i and π_i require it. Since the task situation parameters will be fixed when the organization is in operation, any adjustment in workload must be made through changes in the way the task is executed. If the values of λ_i are viewed as variable, then the organization member might use them to adapt his workload demands so that they are within limits. Formally, the determination of whether such an adaptation can succeed is made according to whether

$$\forall \omega \in \bar{\Omega} \exists \lambda_i \text{ s.t. } w_i(\theta_i^c, \lambda_i, \omega_i, \pi_i) \leq \bar{w}_i \quad (4.12)$$

The determination of whether such adaptation will succeed requires consideration of behavior as the organization member transitions from one operating point to another.

Thus a number of evaluation criteria for the nominal organization design may be of interest. If the design satisfies all criteria, i.e. if it meets the organization design goals, then the design process has been completed as far as the methodology takes it. If, however, the nominal design does not meet design goals, then modifications are necessary.

4.1.3 Modification of Nominal Design - Step I

Suppose that evaluation of the nominal organization design in Step H has determined that a number of flaws in the design exist. The question then arises as to what modifications should be made so that the design becomes satisfactory. Ideally, the nature of the design's flaws will indicate which of several options might be pursued to modify the design. This section discusses several types of modification, each of which requires a return to an earlier methodology step. The process of selecting one of these options, given the organization's deficiencies, is Step I of the methodology. Though little will be said in a general way on how to make such a selection, each modification option discussed is motivated by a particular type of deficiency in design.

Change in Solution Concept

If the nominal design is deficient because of its sensitivity to variation in environmental characteristics ω , then it may be appropriate to alter the solution strategy for Problem CNO. In particular, if ω can be assumed to be an element of a set $\bar{\Omega}$, then it may be desirable to adapt a minmax solution approach. Formally, Problem CNO can be modified to be

Constrained Nominal Organization - Minmax Problem (CNO-M)

$$\begin{aligned} \min_{\theta, \lambda} \quad & \left\{ \max_{\omega \in \bar{\Omega}} \left\{ J_0(k(\theta, \lambda, \omega, \pi), \omega) \right\} \right\} \\ \text{s.t.} \quad & w_i(\theta_i, \lambda_i, \omega_i, \pi_i) \leq \bar{w}_i \end{aligned}$$

The values of θ and λ that solve Problem CNO-M establish an upper bound on performance, given that ω remains within $\bar{\Omega}$. Therefore, if this performance value is acceptable with respect to design goals, it is assumed that variation in ω will not induce a worse than acceptable organization performance.

Selecting this modification option does not require any changes in the results of Phases I and II of the design process. Rather, it changes the mechanism for integrating design elements so that it incorporates a degree of robustness with respect to ω .

Change in Information Processing Options

A second option for modifying an organization design is to alter the way in which an organization member performs the information processing required by his task. Changes of this type might include providing the member, through training, with a different method for processing inputs into outputs. It might include a change in the processing methods that were originally given. It may even include a restriction on the use of processing methods so that they are executed only in certain situations.

Modification in the information processing characteristics of an organization member is an option that might be useful when the member is subject to overload because of changes in π_i and ω_i . By providing additional processing options or revising existing ones, the designer ensures that organization members will be able to adjust their respective induced workloads, should such adaptation be required. However, since an information processing model is a description of how a human performs a particular task, it may or may not be possible to alter how that processing is performed. To the extent that processing is done according to specific training and/or involves a selection among processing alternatives, it is more likely that the designer can actually carry out changes in a member's information processing behavior. Any changes require a return to Phase II of the methodology, in particular to Step F. Execution of the design process then continues forward from this point.

Change in Task Situation

A third option for design modification is to alter the task situation of an organization member. This option may be most appropriate to use

when the workload of a member is at a generally high level with respect to the limit \bar{w}_i , or where the solution to Problem CNO places task situation parameters at extreme values. Such a situation indicates that there may not be a good match between the task situation, the workload it induces, and the operation of the organization.

Changes in the task situation are changes in the physical aspects of a decision rule's implementation. A different display or an alternate physical response mechanism are examples of such changes. Included in this type of modification is the addition of equipment that functions as a "decision aid", i.e. that effectively pre-processes a member's inputs so that a reduction in workload might result. Changes in task situation return the designer to Step E. Once a change has been made, the set of task situation parameters must be revised. The design process then continues forward with re-consideration and possible revision of the information processing model.

Change in Analytic Organization Structure

The most fundamental change in organization design is made by modifying the basic organization structure. This type of change may be necessary if the current nominal design is determined to be wholly unsatisfactory with respect to performance goals. Such a situation might arise if the designer initially misjudged the amount of workload that would be induced by the overall organization task, and divided it among too few organization members. That is, while the outcome of Phase I (which is normative) might have indicated that organization performance would meet design goals (Step D), the addition of workload constraints in Phase II and their integration into the overall design could severely limit the best achievable level of performance. Additional organization members may thus be required so that each will have a lower workload and can more nearly perform their tasks according to their respective job descriptions.

A change in organization structure returns the designer to Phase I in

the design process, and in many respects represents a re-execution of the entire methodology. Depending on the specific modification made, however, it may be possible to retain some of the results and models already obtained when executing Phase II. For example, if organization members are to be added, a possibility for doing this is to divide one of the original tasks into two sub-tasks, leaving the other members' tasks unchanged.

Summary

This section has discussed a variety of options for the modification of a nominal organization design that has been found to be unsatisfactory. This list is certainly not exhaustive, but it did include options that return the designer to different points in the design process for iteration on previously executed steps. Though each option has been motivated by a specific design deficiency, an exclusive association is not necessarily implied. The selection of which option to use is left to the judgement of the designer as he weighs possible alternatives to modifying a nominal design to meet design goals.

4.2 Execution of Phase III - Example

This section continues the design process for the inspection organization by exercising each of the methodology steps in Phase III to integrate the design elements developed in previous chapters. To simplify the discussion, however, a successful integration of design elements pertaining to the second member is presumed, and attention is focused on the first member. In the following sections, Problem CNO is formulated and solved for the inspection organization (Step G). Next the nominal design is evaluated (Step H) with respect to the criteria derived from the design problem conditions. The results of this evaluation indicate a design weakness, and two modification options are considered to correct the deficiency (Step I). For each option, the design process is iterated on previous methodology steps, and a satisfactory nominal design is finally obtained.

4.2.1 Obtaining Nominal Design

Review of Design Elements and Formulation of Problem CNO

In Chapter 2, a two-member analytic organization structure was specified to accomplish the inspection task. Decision rules for each member were derived and had the form of threshold tests. In Chapter 3, a task situation for the first member's decision rule was established, which incorporated a visual display and mechanical response buttons. In the information processing model for this task, input/output behavior included a probability of error in judging diffraction pattern orientation with respect to the threshold. A workload measure was derived using average processing time. Both components of the model were dependent on the threshold position. (See Figure 3.3 and eq.(3.18) for details of these dependencies.)

Given these design elements, the problem of obtaining a nominal design can now be formulated. (The absence of an information processing model for the second member is addressed subsequently.) Following the discussion of the previous section, and taking advantage of the decomposition possible within the analytic organization structure (see chapter two), Problem CNO takes the form of a three-stage constrained optimization problem:

Inspection Organization Nominal Design Problem (NO-I)

$$\text{Stage 3: } V_3^C(P_3) = [0 \ 1 \ 1 \ 0] \cdot \bar{P}_3$$

$$\text{Stage 2: } V_2^C(P_2) = \min_{\theta_2, \lambda_2} \left\{ V_3^C(P_3) \right\}$$

$$\text{s.t. } w_2(\theta_2, \lambda_2, \pi_2, \omega_2) \leq \bar{w}_2$$

$$\text{Stage 1: } V_1^c(P_1) = \min_{t_1} \left\{ V_2^c(P_1) \right\}$$

$$\text{s.t. } w_1 = R_0 \cdot \bar{t}_{p11}(t_1) \leq 1$$

As with the solution for the decision rules, Problem CNO-I is one of sweeping the terminal cost $V_2^c(P_1)$ back through the stages. Here, however, the constraints on workload have been added at each stage that involves an organization member. Since no information processing model has been specified for the second member, his workload constraint has been shown using the general representation. For the first member, however, a particular model is available, and the optimization at stage 1 is with respect to the first member's single task situation parameter, t_1 .

In the formulation of Problem CNO-I, the quantity \bar{P}_3 designates a vector representation of the joint distribution P_3 :

$$\bar{P}_3 \triangleq \begin{bmatrix} p(v = 0, H = H^0) \\ p(v = 1, H = H^0) \\ p(v = 0, H = H^1) \\ p(v = 1, H = H^1) \end{bmatrix} \quad (4.21)$$

Solution to Problem CNO-I

In principle the solution of Problem CNO-I proceeds by solving the problem at stage n in terms of P_n . When Stage 1 is reached, it will be necessary to make a reverse sweep to select the task situation and information processing parameters θ_1^c and λ_1^c . In order to simplify the illustration of Phase III, however, the solution of Problem CNO-I will not be pursued in detail. Instead, attention will be focused on Stage 1. To do this, assume that the solution at Stage 2 is such that

$$V_2^c(P_1) = [0.03 \ 0.15 \ 0.15 \ 0.10] \cdot \bar{P}_3 \quad (4.22)$$

where \bar{P}_2 is the vector representation of P_2 analogous to \bar{P}_1 . In words, the assumption made in eq.(4.22) is that placement of θ_2 and λ_2 is such that the characteristics of the second member's test are constant, given the values of u and H . In particular, if the first member incorrectly indicates the value of H , the second member will with probability 0.15 also indicate the incorrect value. Furthermore, if the first member correctly indicates that $H = H^0$ or H^1 , then the second member's test will agree with this indication with probability 0.97 or 0.90, respectively.

Since the a priori likelihood of H is assumed to be known and fixed during the course of obtaining a nominal design, the above assumption leaves only the Stage 1 constrained minimization unresolved:

Problem CNO-II (Inspection Organization's First Stage)

$$\min_{t_1} \left\{ V_2^C(P_2) \right\} = \min_{t_1} \left\{ [0.03 \quad 0.15 \quad 0.15 \quad 0.10] \cdot \bar{P}_2 \right\}$$

$$\text{s.t. } R_0 \cdot \bar{t}_{p_{11}}(t_1) \leq 1$$

Problem CNO-II is the problem on which the execution of Phase III will be focused. While it does not include explicitly the consideration of the full organization, it will nevertheless be sufficient as a basis for demonstrating in a concrete way the considerations required in Phase III.

It is convenient to discuss the solution to Problem CNO-II in geometric terms using the framework developed in Appendix A. Specifically, for given $p(H)$, all possible values of P_2 (and therefore \bar{P}_2) can be represented in a two-dimensional space with basis selected as

$$p(u = 0, H = H^0) \triangleq p_{00} \quad (4.24)$$

$$p(u = 1, H = H^1) \triangleq p_{11} \quad (4.25)$$

For the present case, the nominal distribution on H is given as $(p_0, p_1) = (0.2, 0.8)$ and the locus of possible (p_{00}, p_{11}) values is as shown in Figure

4.1. The locus is generated parametrically as t_1 ranges from 0 to 180.

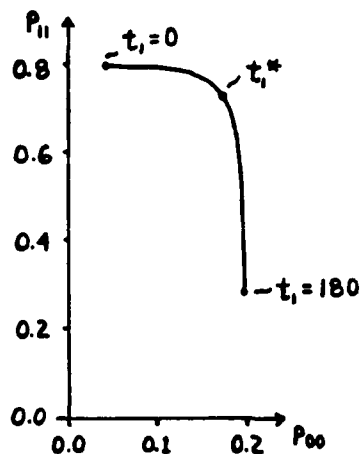


Figure 4.1 Locus of (p_{00}, p_{11}) Values for First Member Inspection Task

Note that as $t_1 \rightarrow 0$, the likelihood that the first member will select $u = 1$ increases and the likelihood that $u = 0$ decreases. The opposite is true as $t_1 \rightarrow 180$.

Problem CNO-II is solved by selecting from the possible \bar{P}_2 values represented in Figure 4.1 the one that minimizes $V_2^C(P_2)$. If P_2 is expressed in terms of p_0 , p_1 , p_{00} , and p_{11} , $V_2^C(P_2)$ becomes

$$V_2^C(P_2) = 0.15 \cdot (p_0 + p_1) - 0.12 \cdot p_{00} - 0.05 \cdot p_{11} \quad (4.26)$$

As is evident from eq.(4.26), constant V_2^C loci in the (p_{00}, p_{11}) plane are linear. Such loci are shown in Figure 4.2 for several values of V_2^C . Neglecting any effect of the constraint on processing time, the best performance possible corresponds to where the V_2^C loci and the P_2 arc are tangent. As a consequence of the convexity of the P_2 arc (see Appendix A and [27]), a single such tangent point exists.

Not all t_1 values are feasible when the workload constraint is taken into account, however. This is shown in Figure 4.3(a), where a constant $(R_0)^{-1} = \bar{t}_{p11}$ locus has been superimposed on the $\bar{t}_{p11}(t_1)$ model. Because of the constraint, any value of \bar{t}_{p11} greater than $(R_0)^{-1}$ is not feasible, which means that an interval of t_1 values must be removed from

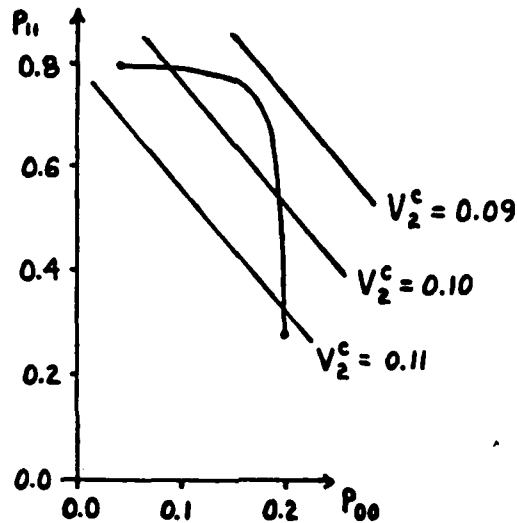


Figure 4.2 Illustration of Constant V_2^C Loci in (p_{00}, p_{11}) Plane

consideration as solutions. Figure 4.3(b) shows how this restriction affects P_s values. In this situation, the solution to Problem CNO-II is where the constant V_2^C locus of lowest value intersects the feasible P_s arc in Figure 4.3(b). This occurs at point B, which determines the solution value t_1^C , as depicted in Figure 4.3(a).

A nominal design for the organization now exists. The next step is to evaluate it with respect to the goals and operating conditions that were given in Step A as part of the design problem.

4.2.2 Evaluation of Nominal Inspection Organization Design

From the design goals and operating conditions outlined in the statement of the organization design problem, several specific criteria can be formulated against which to assess whether a design is satisfactory. One is to verify that the overall probability of inspection error is less than 0.1, which means that fewer than 10% of the inspection decisions will be incorrect. From Figure 4.3(b), it is evident that the nominal design operating point meets this requirement, since the $V_2^C = 0.1$ locus is below point B.

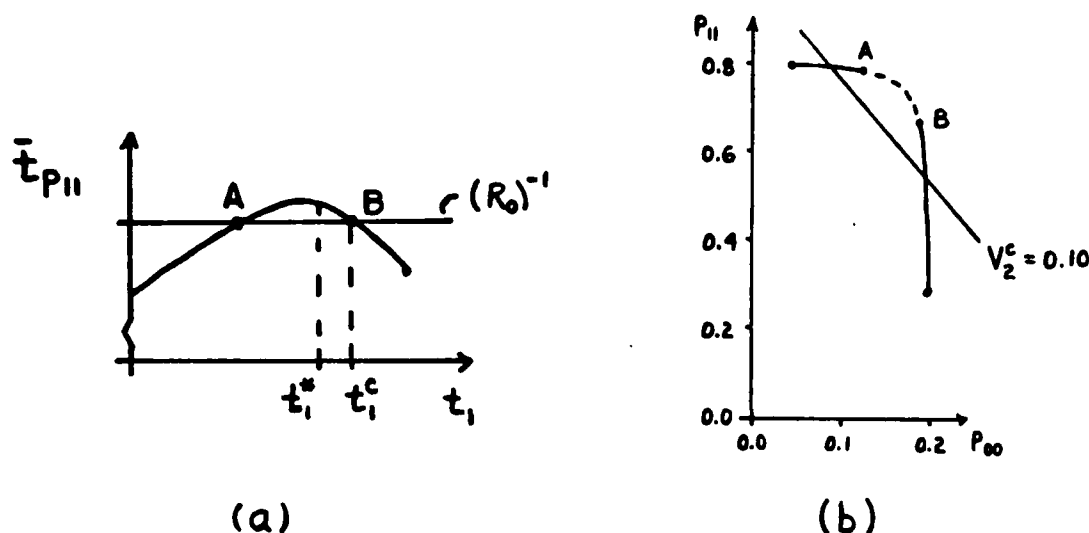


Figure 4.3 Effect of Constraint on Problem CNO-I1 Solution

A second criterion is whether inspection performance remains satisfactory when the fraction of unusable wafers varies. Specifically, a range of ± 0.05 about the nominal value of 0.20 is anticipated, and it is required that the maximum error rate of 10% be maintained for any value of p_0 in the interval $[0.15, 0.25]$. Assume, for purposes of illustration, that changes in p_0 do not affect the characteristics of the second member's operation. Then the assessment of whether the nominal design is sensitive to changes in p_0 can be made in terms of the P_1 locus. Figure 4.4 shows loci of P_1 values for $p_0 = 0.15, 0.20$, and 0.25 . The qualitative characteristics are the same for each. In particular, point B in each locus corresponds to where $t_1 = t_1^c$. Note that t_1^c represents the solution to Problem CNO-I1 only for $p_0 = 0.2$. It may or may not be the solution to a reformulated Problem CNO-I1 with $p_0 = 0.15$ or 0.25 . What is shown in Figure 4.4 is how the first member's operating point changes in the (p_{00}, p_{11}) plane when t_1 is fixed at t_1^c and p_0 changes. The locus joining all points labelled B corresponds to all the operating points when $p_0 \in [0.15, 0.25]$. Since this locus lies entirely above the $V_2^c = 0.10$ line in the (p_{00}, p_{11}) plane, the nominal design meets the criterion for being insensitive to variation in the likelihood of unusable wafers.

Finally, a third criterion is whether the nominal design can tolerate any variation in the conveyor belt speed. The nominal speed is such that

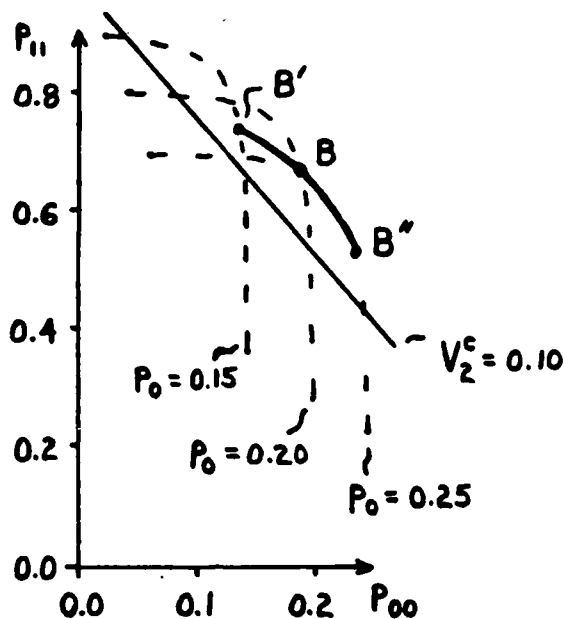


Figure 4.4 Operation of Nominal Organization as p_0 Varies

R_0 inspections are required per minute, but this rate is subject to variation of $\pm 10\%$. It is required to maintain satisfactory organization operation in spite of changes within this range. Again, it is assumed that the second member is able to cope with such a variation, and attention is focused on the first member. The range in R values is illustrated in Figure 4.5, which shows possible $(R)^{-1}$ values in comparison

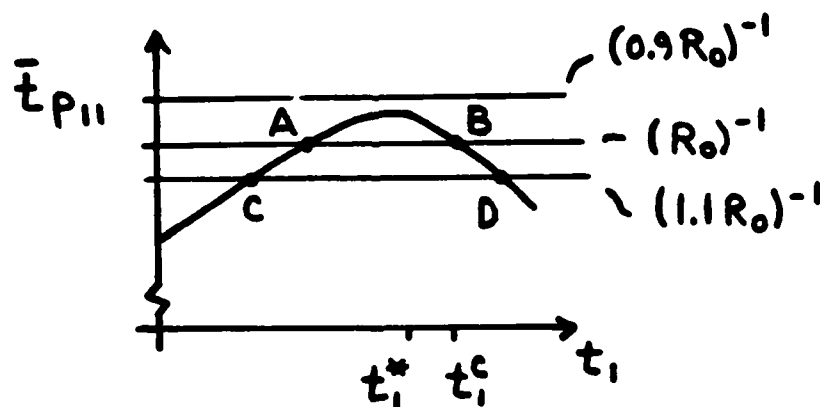


Figure 4.5 Comparison of R Range with First Member Processing Time

with the average processing time characteristics of the first member. If $t_1 = t_1^c$, it is evident from Figure 4.5 that if R decreases the organization member will continue to operate as desired. However, since

the nominal design places the member at an operating point where $\bar{t}_{p11} = (R_0)^{-1}$, if R increases the member will be overloaded. Moreover, it is not clear how the member will react in this situation. He may react by continuing to inspect wafers as well as possible, but with a higher error rate than β , or he may react by simply giving up at his task. This uncertainty in organization operation constitutes a deficiency in the nominal design.

In sum, the foregoing has been an evaluation of the nominal design obtained as the solution to Problem CNO-II in section 4.2.1. The design was found to be satisfactory with respect to two criteria that were derived from the design goals and conditions set forth in Step A. A third criterion, that of insensitivity to conveyor belt speed, was not met by the design, however. Thus re-consideration and modification of the design are necessary in order to remedy the deficiency.

4.2.3 Modification of Inspection Organization Design

There are a number of design modifications that might be made in an attempt to resolve the difficulty discovered in the previous section. The basic problem is that the first organization member's nominal operation point has been placed at his processing load limit, and that no provision has been made either to describe his behavior when overloaded or to ensure that he never becomes overloaded. The following paragraphs discuss two possible modifications to the design that address this issue.

Change in Solution Concept for Nominal Design

One strategy for improving the first member's tolerance to variation in processing load is to design the organization so that members are deliberately underloaded, and thereby create a processing load safety margin. In the present situation, this would correspond to using the fastest conveyor belt speed when determining the placement of t_1 . This strategy represents a modification in the solution approach to Problem

CNO; it is in fact a minmax type of strategy. The modification is one that returns the designer to Step G. Rather than formally stating and solving the modified version of Problem CNO-II that reflects the change in solution concept, the effect on the nominal design solution will be discussed directly in terms of the (p_{00}, p_{11}) plane.

In Figure 4.5, points C and D correspond to where R is at its maximum value and where the member is at his processing load limit. As is evident from the figure, the change in solution approach further restricts the set of feasible t_1 values. The corresponding locus of P_2 values are shown in Figure 4.6. The solution point for the nominal design still corresponds

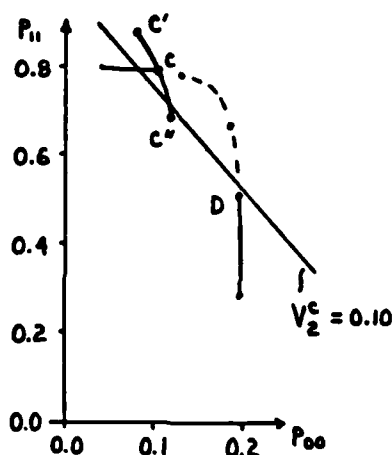


Figure 4.6 Operation in (p_{00}, p_{11}) Plane with Minmax Modification

to where the lowest value V_2^C contour intersects the locus. According to the figure, this is point C, which represents a new nominal design. Since the nominal design has changed, re-evaluation is necessary to see if the three criteria are met. The first, that of having organization detection error less than 0.10, is satisfied, as is evident from Figure 4.6. The second criterion, which is that of insensitivity to p_0 variation, is a different matter, however. Figure 4.6 shows the locus of points corresponding to operation at the revised nominal design point as p_0 varies. Points C' and C'' correspond to where $p_0 = 0.15$ and 0.25, respectively. According to the figure, as p_0 moves toward 0.25,

organization inspection error rate exceeds the 0.1 level, which is unacceptable. Thus the modification made to the original design has not been successful and the design process returns to Step H, where a different modification can be tried.

Change in Information Processing Model

A second strategy for improving the first member's tolerance to processing load variations is to incorporate a mechanism whereby the member can adapt his processing load to keep it within limits. One possibility for doing this would be to provide an additional processing option that has a lower workload. In this way, if the conveyor belt speed increases, the member can simply use the lower workload option on a greater percentage of the inspections. This modification to the organization design requires a change in the member's information processing model, which returns the design process to Step F.

Suppose that the first member's added processing option is the option to bypass a particular inspection, leaving the decision entirely to the second member. When the first member chooses to exercise this option, he is instructed (somewhat arbitrarily) to indicate that the wafer is not defective, i.e. to respond with $u = 1$. Assume that executing this bypass option requires t_g seconds, where t_g is substantially less than the average time required to complete a diffraction pattern test. The components of the information processing model for the bypass option are given as

$$\text{Input/Output: } k_{12}: Y_1 \rightarrow u = 1 \quad (4.27)$$

$$\text{Workload (Processing Time): } \bar{t}_{p12} = t_g \quad (4.28)$$

Based on the discussion in section 3.3, the two options are combined as follows into a revised information processing model for the member. If q_1 denotes the fraction the bypass option is used, then the conditional input/output distribution \bar{k}_1 is given as

$$\bar{k}_1 = (1-q_1) \cdot \bar{k}_{11} + q_1 \cdot \bar{k}_{12} \quad (4.29)$$

Furthermore, assuming that there is no additional processing time required to switch between options, the revised workload measure is given as

$$w_1 = R \cdot [(1-q_1) \cdot \bar{t}_{p11}(t_1) + q_1 \cdot \bar{t}_{p12}] \quad (4.30)$$

Eq.(4.28) and (4.29) signify that Phase II has been completed for this design revision. Since q_1 represents a selection among options made by the member, an information processing parameter has been introduced:

$$\lambda_1 = (q_1) \quad (4.31)$$

Solution for a revised nominal design will now have to determine not only a value for t_1 but also one for q_1 .

Integrating the modified design elements to obtain a revised nominal design is done by reformulating Problem CNO to include the changes made. Since the change made pertains only to the first member, the second member's operating characteristics will remain the same. In particular, it is still true that

$$V_2^C = [0.03 \quad 0.15 \quad 0.15 \quad 0.10] \cdot \bar{P}_2 \quad (4.32)$$

Therefore a revised nominal design is obtained as the solution to a modified Problem CNO-II:

Problem CNO-II'

$$\min_{t_1, q_1} \left\{ V_2^C(P_2) \right\}$$

$$\text{s.t. } R_0 \cdot [(1-q_1) \cdot \bar{t}_{p11}(t_1) + q_1 \cdot \bar{t}_{p12}] \leq 1$$

Note that the previous nominal design is still possible, i.e. $t_1 = t_1^c$ and $q_1 = 0$ is a solution to Problem CNO-11'. However, the additional degree of freedom represented by q_1 may be used to advantage in specifying a nominal design. Figure 4.7 illustrates the region of feasible P_2 values

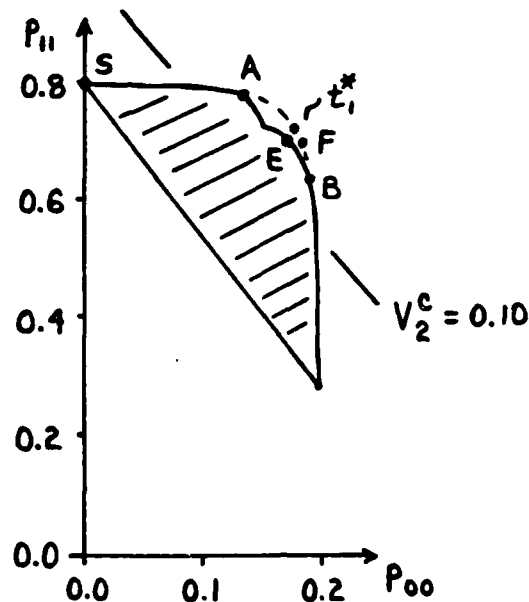


Figure 4.7 Solution of Problem CNO-11'

as they appear in the (p_{00}, p_{11}) plane. Briefly, exclusive use of the bypass option corresponds to operation at point S. All other possible operating points are determined by taking the convex combination of point S with any point on the original P_2 arc (which is now the locus where $q_1 = 0$). The constraint on workload eliminates some of these combinations from feasibility, however, which accounts for the non-convexity of the regions in Figure 4.7. See Appendix A for a more detailed discussion of how constraints such as eq.(4.30) map to feasible P_2 values as represented in the (p_{00}, p_{11}) plane.

As before, the solution to the problem, in geometric terms, is where the smallest equi- V_2^c contour intersects the region of feasible P_2 values. According to the figure, this occurs at point E. Since point E is not on the original P_2 locus, it corresponds to a point where $q_1 \neq 0$. That is, the nominal design makes use of the bypass option. The advantage is that the value of t_1 can then be set closer to the decision rule threshold t_1^* , which means that if the member bypasses a few inspection tests he can use

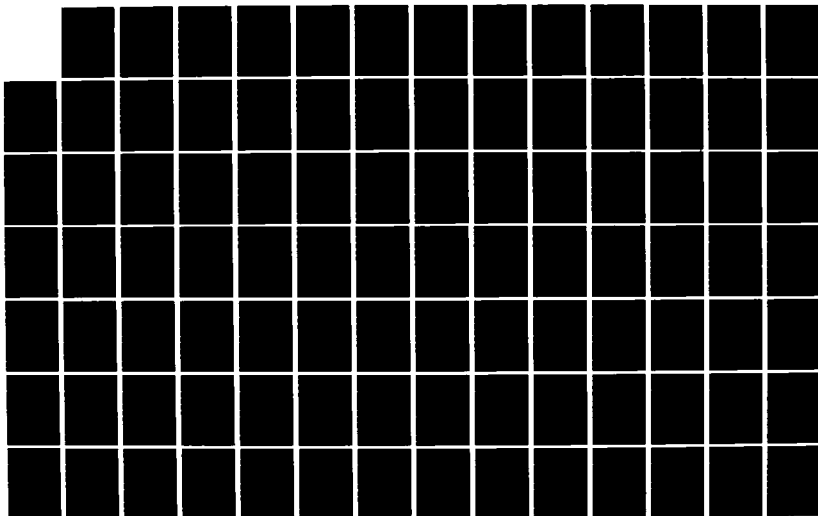
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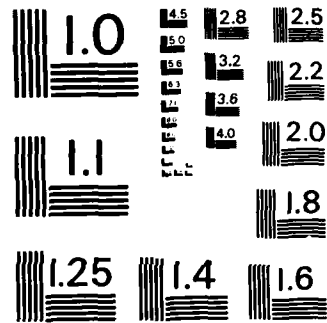
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a higher quality threshold on the diffraction tests that he does make. Implementation of the revised design means that t_1 is fixed at its revised value. It also means that the organization member is either to be trained to bypass the fraction q_1^c , or is predicted to bypass that fraction in order to maintain workload within limits.

Given the position of point E in Figure 4.7, it is evident that the current nominal design meets the criterion of having less than 10% inspection error. Figure 4.8(a) illustrates how the modified organization

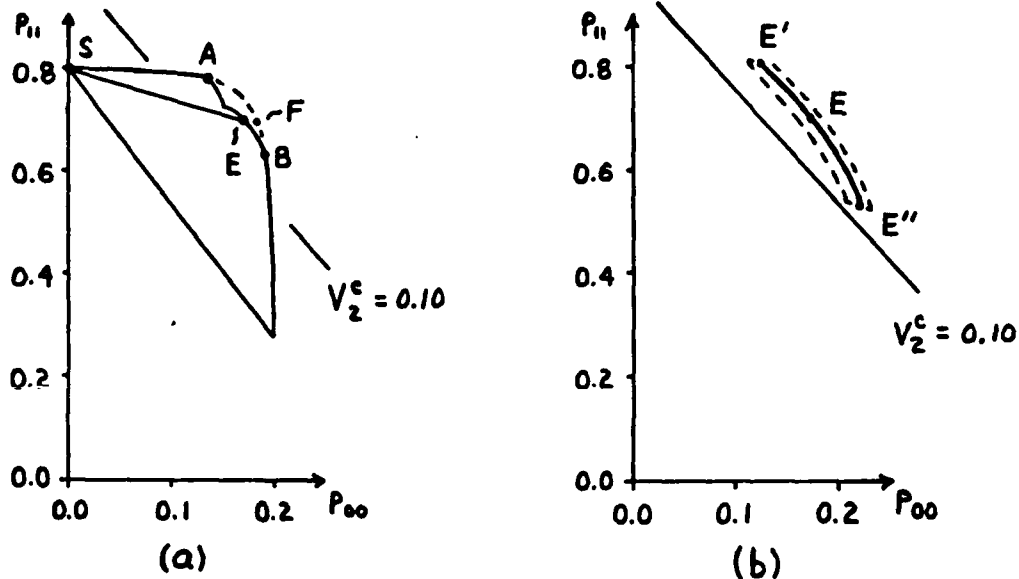


Figure 4.8 Operation in (p_{00}, p_{11}) Plane with Additional Procedure

will operate as the conveyor rate R varies, again assuming that changes in R do not affect the second member. Nominally, i.e. with $R = R_0$, operation is at point E. As R_0 increases to $(1.1)R_0$, the member can compensate by bypassing more inspections, as was intended by providing such an option. This corresponds to moving the operating point along a line from point E to point S. If the operating point on this line corresponding to $R = (1.1)R_0$ is such that $V_1^c < 0.1$, then the organization meets the third evaluation criterion. This is indicated to be the case in Figure 4.8(a). Note that if $R = (0.9)R_0$, the member need not bypass so many inspections. In this latter case operation moves toward point F in Figure 4.8(a), which produces performance that is better than the nominal design.

Finally, there is the issue of whether the current nominal design satisfies the criterion of insensitivity to p_o variation. In Figure 4.8(b) the arc from E' to E'' shows the locus of P_z values that are possible when p_o ranges within the interval $[0.15, 0.25]$, with $R = R_o$. Since this arc is entirely above the $V_z^C = 0.1$ contour, the second criterion is satisfied. Furthermore, Figure 4.8(b) also shows the region of operating points possible as both p_o and R range within their respective intervals. This entire region is above the $V_z^C = 0.1$ contour, which means that the current nominal design is robust with respect to simultaneous variations in p_o and R . Thus the second modification to the original design has been successful; a satisfactory nominal organization design has been obtained for the inspection task.

Summary

This section has exercised the modification step (Step I) of the methodology. The first modification proposed to the original design was a change in the solution concept for obtaining a nominal design. A minmax approach was adopted. This required a return to Step G of the design process. After obtaining a revised nominal design, however, evaluation in Step H found it still to be unsatisfactory. A second iteration on Step I was then executed and a different modification was suggested, that of providing the first member with an additional procedure. The design process then returned to Step F in order to incorporate this change, and a revised information processing model was obtained. Then, in Step G, a second revised nominal design was obtained. This one differed qualitatively from the original in that a strategy of sometimes bypassing an inspection was found to be a characteristic of the design. Evaluation of this second revised nominal design was then made, and it was found to be satisfactory with respect to the three criteria being used. The design process was then terminated, since a satisfactory inspection organization design had been obtained.

V. EXECUTION OF METHODOLOGY - AN EXISTENCE PROOF

5.1 Introduction

Although an example organization design using the methodology has been partially carried out in the previous chapters, the discussion of the methodology so far has been largely at the conceptual level. In this chapter, a specific design problem is stated and the methodology is used to determine a complete nominal organization design. The purpose in doing so is twofold. First, it provides another example to illustrate the approach to organization design suggested in this thesis. More importantly, however, is that the completed design can be operated as a test and partial validation of the design approach.

The extent to which the organization operates as designed provides an indication as to the viability of the design approach. This is in fact a key point of the chapter, and even of the entire thesis. Previous chapters have proposed an approach to integrating human limitations into analytic organization models. This chapter describes the application of that approach to a specific design problem, which results in a design that operates as predicted. As such, this demonstration serves as an existence proof for the applicability of the conceptual development presented in previous chapters to realistic human team decisionmaking.

The chapter is organized as follows. In the next section, Phase I of the design is executed. A design problem is stated (Step A), an analytic organization structure chosen (Step B) and decision rules that represent ideal human behavior are obtained (Step C). In the third section, implementations of these decision rules are devised, resulting in a task situation and an information processing model for each organization member (Phase II). In section four design elements are integrated to obtain a satisfactory nominal design. Section five discusses several hypotheses about the behavior of the organization, and a laboratory version of the organization is exercised to test these hypotheses. Finally, a summary section concludes the chapter.

5.2 Analytic Organization Structure

5.2.1 Statement of Design Problem

Consider the situation shown in Figure 5.1, which is intended to

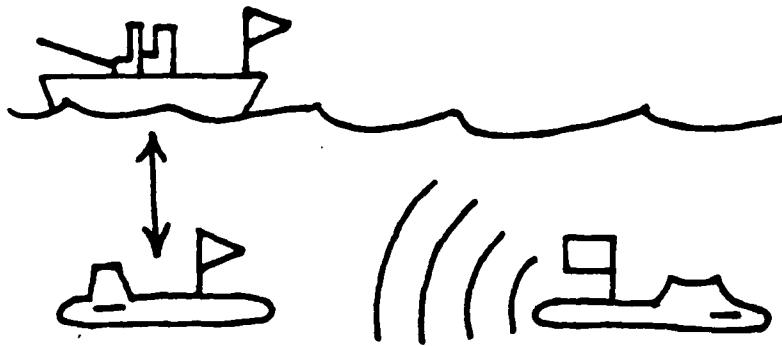


Figure 5.1 Design Situation

capture some interesting aspects of a particular command and control situation. It is desired that a decision regarding the presence or absence of a target be made every τ_0 time units. There are two platforms involved, and each receives an observation pertaining to a target every τ_0 time units. The observations are related to signal energy received; if a target is present, there is generally a higher level of energy in each observation. The fidelity of platform observations is not the same, however. The submerged platform has a signal-to-noise ratio that is approximately 25% lower than that of the surface platform.

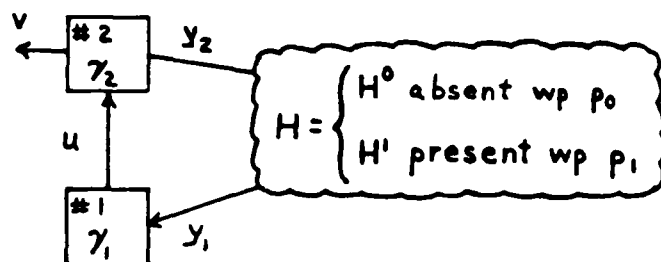
It is desired that a coordinated detection decision be made, i.e. the information in each set of observations is to be fused in some fashion. However, due to security considerations, communication between platforms is severely limited. In addition, there is to be a maximum delay of τ_d time units between the arrival of a set of observations and the detection

decision associated with that set. Both τ_0 and τ_d are subject to approximately a $\pm 5\%$ variation in their nominal values, and it is desired that execution of the detection task not be sensitive to such variations. Finally, the detection error rate is to be as small as possible, but to be at all satisfactory, there must be less than 15% errors when the target is present with probability 0.6.

5.2.2 Specification of Analytic Organization Structure

The description above is presented to the organization designer. To begin the design, the statements made must be translated into analytic terms that specify the basic form of the organization, and that are adequate representations of design requirements. This process requires choices by the designer, some of which are matters of interpretation. Many such choices will be made in the course of completing the design at hand. There is no claim made that the nominal design obtained is unique. Indeed, depending on the choices made, it is possible to use the design methodology on the same design problem and arrive at many different designs. In the development that follows, some choices have been made for convenience. Others, however, have been made so that simplicity of structure might be retained for purposes of exposition. Still others have been made so that the organization that results is capable of operation in a variety of distinctive modes.

In form, the organization will be specified to have two human members, one on each platform. Their interconnection will be as shown in Figure 5.2, which also summarizes features of the analytic model to be used. The a priori likelihood of H , which is the target's presence or absence, is modeled by the probabilities p_1 and p_0 , respectively. The design will proceed under the assumption that $p_1 = 0.6$. Observations made by each platform are assumed to be conditionally Gaussian and independent from one interval to the next. Using the quantity $\Delta m/\sigma$ as the measure of signal-to-noise, the fact that the surface platform has a higher



$$u, v \in \{0, 1\} \quad m_{i1} > m_{i2}$$

$$p(y_i | H = H^k) \sim N(m_{ik}, \sigma_i^2)$$

Figure 5.2 Analytic Organization Structure for Detection Task

observation fidelity is modeled by assuming that

$$\left(\frac{m_{11} - m_{10}}{\sigma_1} \right) = 0.75 \left(\frac{m_{21} - m_{20}}{\sigma_2} \right) \quad (5.1)$$

Within the structure, the first organization member is presented with the observation y_1 and must decide between one of two indications to pass as the value of u to the second organization member. The choice of symbols for u is limited in order to minimize communication between platforms. In particular, the specified structure requires communication of a single bit of information every τ_0 time units. The received value of u is used by the second member, along with the observation that has been made at the surface platform (y_2), to arrive at a detection decision v for the organization.

It is assumed that detection decisions are made independently from one set of observations to the next. That is, the organization will not possess memory in the sense of having to consider and assess sequences of observations. (This may be done outside the present organization, however, perhaps by another agent who accumulates the indications v over time.) Thus the organization model is static in nature, but the detection task that it represents is to be repeated every τ_0 time units.

The analytic organization structure is now in place. A two member

tandem distributed detection network has been specified that is analytically similar to the inspection organization considered in Chapter 2. The sets Γ_i , U_i , V_i , Y_i , and Z_i are the same for both structures. A different set of environmental characteristics are of interest for the detection task, however. From the organization's point of view the quantities τ_o and τ_d are subject to variation and are therefore included as elements of ω :

$$\omega = (\tau_o, \tau_d) \quad (5.2)$$

5.2.3 Decision Rules for Organization Members

Given the analytic organization structure, the next step is to select the decision rules for each member. From the statement of the design problem, the natural performance measure of the organization is the probability of detection error, i.e.

$$J_o(\gamma, \omega) = \text{pr}(\text{target detection error}) \quad (5.3)$$

Minimum J_o is desired, but an additional requirement is that

$$J_o \leq \bar{J}_o = 0.15 \quad (5.4)$$

Eq.(5.4) represents one criterion for evaluating a nominal organization design. A second that can be inferred from the design problem statement is that the nominal design should be insensitive to variations in τ_o and τ_d .

The solution to Problem DR in the present case is identical to the solution in the case of the inspection organization. In particular, since time is not an explicit part of the analytic structure, the solution is not dependent on ω . The decision rules for members are threshold tests:

$$\gamma_1^* : \begin{cases} \text{if } y_1 \geq t_1^* & u = 1 \\ \text{else} & u = 0 \end{cases}$$

$$\gamma_2^* : \text{if } u = j \quad \text{and} \quad \begin{cases} y_2 \geq t_{2j}^* & v = 1 \\ y_2 < t_{2j}^* & v = 0 \end{cases}, \quad j = 0, 1 \quad (5.5)$$

Appendix B contains the details of the solution for the present organization, including the specific values used for all parameters. Use of the decision rules yields a probability of organization error of 0.06, i.e.

$$J_0(\gamma^*, \omega^N) = 0.06 \quad (5.6)$$

This is well within the minimum performance level for a satisfactory design. Phase I of the design can thus be considered complete, and attention can be focused on implementation of the decision rules.

5.3 Decision Rule Implementation

5.3.1 Time Allocation

In the specification of an analytic organization structure, it was not necessary to address how the time available for detection should be allocated between members. In developing implementations for decision rules, however, this allocation is an important consideration. For the present design, the first member will be required to process observations at the same rate that they arrive. That is, he must make a threshold comparison test every τ_1 time units, where

$$\tau_1 = \tau_0 \quad (5.7)$$

This leaves $\tau_d - \tau_0$ time units to communicate u to the second member and

for the second member to complete his processing. Assume that communication time is negligible. Then the second member is required to determine his response in τ_2 time units, where

$$\tau_2 = \tau_d - \tau_0 \quad (5.8)$$

Finally, in order for the allocation made in eqs.(5.7) and (5.8) to make sense it must also be true that

$$\tau_2 \leq \tau_1 \quad (5.9)$$

Otherwise, the second member would be processing at a rate slower than that of arriving observations, which would constitute an unworkable design.

In the sequel, and to a large extent simply for variety, two different interpretations will be given to the quantities τ_1 and τ_2 . The time allocated to the first member will be considered as an average processing rate requirement. Individual observations may differ greatly in the time it takes for them to be processed by the member. So long as the average time taken is such that the member does not fall behind in processing, however, the organization design requirement will be satisfied. By contrast, the second member will be restricted to take no more than τ_2 time units to process any one observation. In practice this will mean that the processing on each observation should take about the same amount of time and have an average of no more than τ_2 . The notion is that the second member is operating under the pressure of a deadline.

Qualitatively, the interpretations given to τ_1 and τ_2 are such that the first member is driven by an input clock, i.e. an outside source is effectively "pushing" the member to complete his required processing. On the other hand, the second member is subject to an output clock; he is effectively being "pulled" by an outside source, perhaps another agent who intends to use the detection decision. If both members operate as envisioned, however, the basic requirements represented by τ_0 and τ_d will be met.

5.3.2 First Organization Member

Task Situation

To implement the first member's decision rule, a physical interface must be devised that is capable of presenting the observations y_1 to the human and of recording his responses u . Furthermore, it must be such that a comparison with the threshold t_1 can be made. The task situation selected to accomplish this is illustrated in the upper part of Figure 5.3. The organization member views the continuous display of a square,

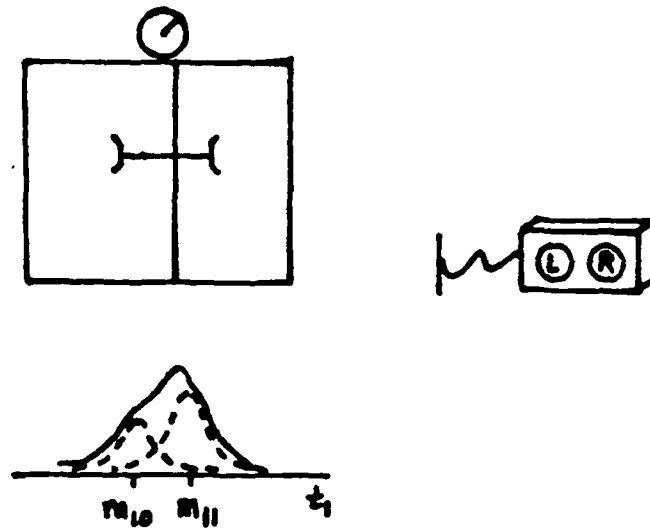


Figure 5.3 First Member Task Situation

where the vertical centerline of the square (not displayed) corresponds to the average of m_{10} and m_{11} . The threshold t_1 is continuously displayed as a vertical line according to its value. Observations are displayed as the pattern shown in the figure, where the horizontal midpoint corresponds to the value of y_1 . For each pattern displayed, the member is to judge whether the midpoint is left or right of the vertical threshold line, and to register the judgement by depressing one of two mechanical, horizontally-arranged buttons. The button depressed is interpreted as the value of u to send to the second member: left button $\Rightarrow u = 0$; right button $\Rightarrow u = 1$.

In the lower part of Figure 5.3, the underlying distribution on observations y_1 is shown. The upper and lower illustrations have been made on a consistent scale so that the range and relative likelihood of pattern positions can be inferred.

As the organization operates, observations arrive to the first member at the rate of one each τ_0 time units. Recall that time has been allocated and interpreted such that the member must keep up with the arrival rate. The dial at the top of the task situation display is provided to aid in meeting the requirement. Its clockwise displacement indicates the number of observations that have arrived and are waiting to be processed. Thus if the member is operating satisfactorily, the dial position will remain near the top (zero).

Information Processing Model

For the task situation shown in Figure 5.3, a model of human behavior is required. This involves both an input/output description, i.e. a characterization of human ability to judge the position of pattern midpoints, as well as a description of the workload induced in making these judgements.

Execution of the task is such that after a period of training the member develops an established mental processing method for judging patterns. The level of proficiency is such that virtually error-free judgements can be made when the member views a pattern carefully. A response of this type will be referred to as a stimulus controlled response (SCR). The input/output behavior when making an SCR can be stated compactly as the mapping k_{SCR} , where

$$k_{SCR}(t_1) : Y_1 \rightarrow p(u) \\ : \begin{cases} \text{if } y_1 \geq t_1 & p(u = 1) = 1 \\ \text{else} & p(u = 0) = 1 \end{cases} \quad (5.10)$$

Assuming that the organization member applies his processing resources in an all or nothing fashion (see chapter three), processing time can be used to develop a measure of the workload induced when making an SCR. The average time to make an SCR, denoted \bar{t}_{SCR} has been observed to vary with threshold position typically as shown in Figure 5.4. The basic

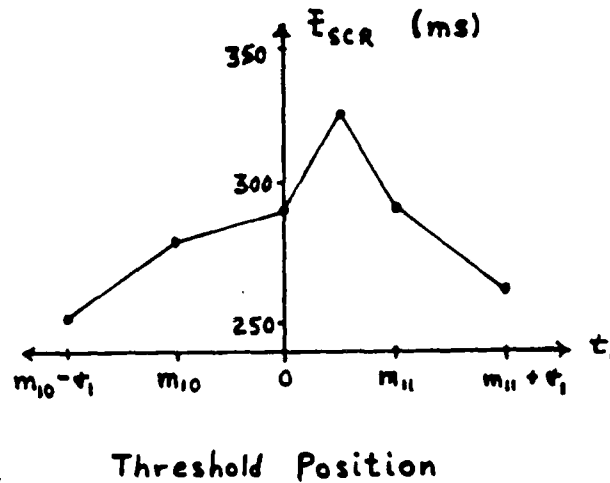


Figure 5.4 First Member SCR Average Processing Time (Typical)

effect is that as t_1 moves to an extreme value (left or right), the a priori uncertainty in the required response is reduced. It therefore takes less time, on average, to make the response. (Appendix B documents the conditions under which the data shown in Figure 5.4 were obtained.) As indicated in the figure, a valid description of SCR behavior is limited to t_1 values in the range

$$t_1 \in [m_{10} - \sigma_1, m_{11} + \sigma_1] \quad (5.11)$$

Furthermore, it is assumed that linear interpolation can be used to obtain \bar{t}_{SCR} at threshold positions for which explicitly observed data are not available.

Following on the discussion in Chapter 3, and assuming that only stimulus controlled responses are made, the quantity

$$(\tau_1)^{-1} \cdot \bar{t}_{SCR} \quad (5.12)$$

can be used as the workload measure. So long as this quantity is less than unity, the member can (on the average) keep pace with observation arrivals, and his input/output behavior will be that of k_{SCR} . When the organization is in operation, t_1 will be fixed and hence \bar{t}_{SCR} is also fixed. If it happens that (5.12) is near unity under nominal operating conditions, then it is possible that variation in τ_1 could cause the member to become overloaded. This is a situation that has not been accounted for in the information processing model thus far, but must be addressed if a satisfactory design is to emerge.

Rather than extend the information processing model to include a description of behavior when overloaded, a mechanism will be provided whereby the member can adjust his workload to keep it within limits, even in view of possible variation in τ_1 . This is accomplished by giving the member a second information processing option. Besides making an SCR, the member will be allowed to ignore the presented pattern and to respond by arbitrarily pushing either button. This type of response will be referred to as a fast guess (FG). The basic idea is that a fast guess will require less time to execute and can thereby be used as necessary to keep workload within limits.

The fast guessing option has input/output and processing time characteristics as follows. It is assumed that, while the member responds arbitrarily, he does so with some fixed bias toward pushing a left or right button. Thus the input/output behavior is given by the distribution \bar{k}_{FG} , where

$$\bar{k}_{FG} : \begin{cases} u = 1 & \text{wp } 1-g_1 \\ u = 0 & \text{wp } g_1 \end{cases} \quad (5.13)$$

The quantity g_1 models the bias toward selecting the left button during a fast guess. Its value can have a significant effect on organization design and operation, as will be discussed later. For the present, however, it is assumed that fast guessing is done with a 50/50 bias, i.e. $g_1 = 0.5$. Finally, because fast guessing is essentially accomplished

independently of pattern characteristics or threshold position, the average time required for an FG, denoted \bar{t}_{FG} , is a constant. Observed fast guessing behavior, as described in Appendix B, establishes that \bar{t}_{FG} is approximately 180 ms.

The information processing options can now be combined to form the overall information processing model. Input/output behavior is described by the conditional distribution \bar{k}_1 , where

$$\bar{k}_1 = (1-q_1) \cdot \bar{k}_{SCR}(t_1) + q_1 \cdot \bar{k}_{FG} \quad (5.14)$$

The quantity q_1 is the fraction of fast guessing. The quantities \bar{k}_1 , \bar{k}_{SCR} , and \bar{k}_{FG} are conditional probability distributions of the form $p(u|y_1)$, with possible additional dependencies on task situation and information processing parameters. The overall average processing time T_{p1} is given as

$$T_{p1} = (1-q_1) \cdot \bar{t}_{SCR}(t_1) + q_1 \cdot \bar{t}_{FG} \quad (5.15)$$

which can be incorporated with τ_1 to obtain the workload measure

$$w_1 = T_{p1} \cdot (\tau_1)^{-1} \quad (5.16)$$

Finally, the member is constrained to operate so that he is not overloaded, i.e.

$$w_1 \leq \bar{w}_1 = 1 \quad (5.17)$$

Eq.(5.14)-(5.15) are basically the Fast Guess model of Yellot [28] adapted for the present task situation. Note that both k_1 and w_1 depend on q_1 and t_1 . If t_1 is set to be t_1^* and q_1 is zero, the member will realize his decision rule exactly, that is, he will perform exactly according to his job description. However, because of workload limitations and environmental uncertainty, it will be of possible advantage to leave t_1 and q_1 as free parameters for the present and to place them at a later

design stage. Consequently, they become elements of θ_1 and λ_1 , respectively. In terms of the general methodology framework, the generalized parameters that pertain to the first member are given as

$$\theta_1 = (t_1) \quad (5.18)$$

$$\lambda_1 = (q_1) \quad (5.19)$$

$$\omega_1 = (\tau_1) \quad (5.20)$$

$$\pi_1 = () \quad (5.21)$$

It is interesting to note that, though it has not been included as such, the fast guessing bias (g_1) is a quantity that qualifies as an information processing parameter, since it represents a choice made that is internal to the human. As a matter of design choice, however, in the present situation the value of g_1 is fixed and will not be part of the optimization process that places θ and λ .

5.3.3 Second Organization Member

Task Situation

The decision rule of the second member will be implemented as the visual information processing task shown in Figure 5.5. Depending on the indication received from the first member, either of two displays are possible. If $u = 0$, then the threshold t_{10} is displayed as a horizontal line and the observation y_1 is displayed vertically displaced according to its value. If $u = 1$, however, the threshold t_{11} is shown vertically and the observation is displaced horizontally according to its value. The specification of horizontal and vertical modes of display has been made, not for practical reasons, but to emphasize the effect of the additional workload required when humans switch between tasks. Both cases are displayed within the same square border, which is visible to the member at all times. Two horizontally arranged mechanical buttons are provided to register the result of the member's threshold comparison test. The left button is to be depressed if the dot is below (t_{10}) or to the left (t_{11})

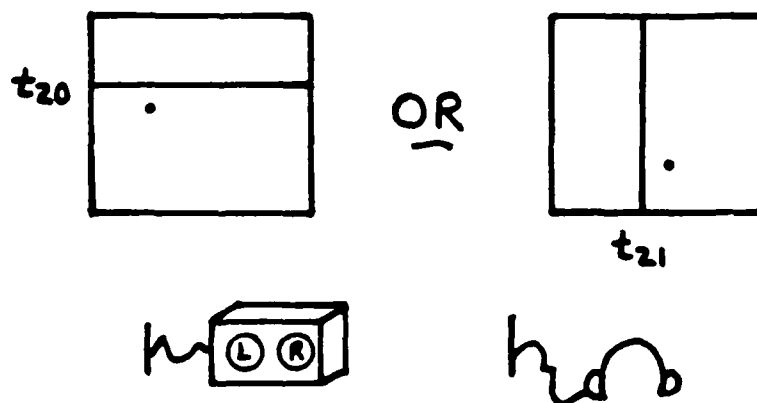


Figure 5.5 Second Member Task Situation

of the threshold, and the right button is to be used when the complementary situations arise.

Recall that the second member is constrained to meet a deadline of τ , time units in processing each observation. An auditory mechanism is used to indicate that the deadline has been reached. When time expires, a "beep" is sounded. Thus the member must perform his task so that either he hears few beeps or hears a beep just as he depresses a button.

Information Processing Model

As with the first member, the information processing model of the second member will include an input/output mapping that describes human behavior. Furthermore, processing time will be used as the fundamental indication of processing load. The model will differ from that of the first member in a key respect, however. Whereas for the first member an overload condition is to be avoided, the second member will be deliberately placed in a situation where he is overloaded. Stated in terms of the workload measure, the member will be operating where the processing time required to complete his task exceeds the processing time

allowed. The model developed will therefore not be of the form where a hard constraint on workload exists. Rather, it will have to take into account how human behavior is affected as the degree of overload changes.

To begin development of the model, consider first the processing time required to do the task. A key parameter that affects the average processing time is the frequency of each threshold's use, i.e. the amount of switching. Denote by q_0 the quantity $p(u = 0)$. Figure 5.6 shows a

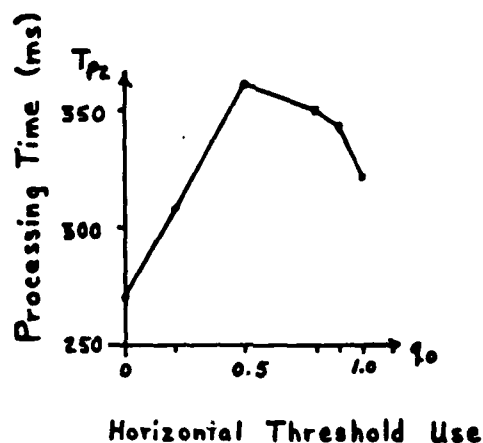


Figure 5.6 Second Member Processing Time (Typical)

typical relationship observed between average processing time T_{P2} and q_0 . The data shown were obtained for the condition where the member was responding as quickly as possible without making any input/output errors (see Appendix B). At the extremes, where no switching is required, it is evident that horizontal threshold comparison tests ($q_0 = 1$) take longer than vertical threshold comparison tests ($q_0 = 0$). In between, there is considerable overhead required in terms of processing time to switch thresholds. This is because the member must re-orient himself as to the proper correspondence between the dot's position vis a vis the threshold and the response buttons. It is evident that the amount of overhead is directly related to the relative frequency of switching. [26] proposes a specific model framework in which the effect shown in Figure 5.6 is understood in terms of two processing methods, one for horizontals and one for verticals, plus a specific switching overhead characterization.

Though not incorporated directly here, this framework has influenced the model developed to describe the second member.

Now consider the case where the member is not given enough time to perform his task, i.e. he is overloaded. The result is that errors are made in processing observations, and the error rate is directly related to the amount by which the member is overloaded. The basic effect is known as the speed/accuracy tradeoff and has been studied extensively. In particular, Pew [29] suggests a log-linear relationship between accuracy and processing time in the region of overload, given that accuracy is measured using the so-called odds ratio OR:

$$OR = \frac{\Delta}{\left(\frac{\# \text{ right}}{\# \text{ wrong}} \right)} \quad (5.22)$$

Figure 5.7 plots the OR versus processing time allowed (t_d) on log-

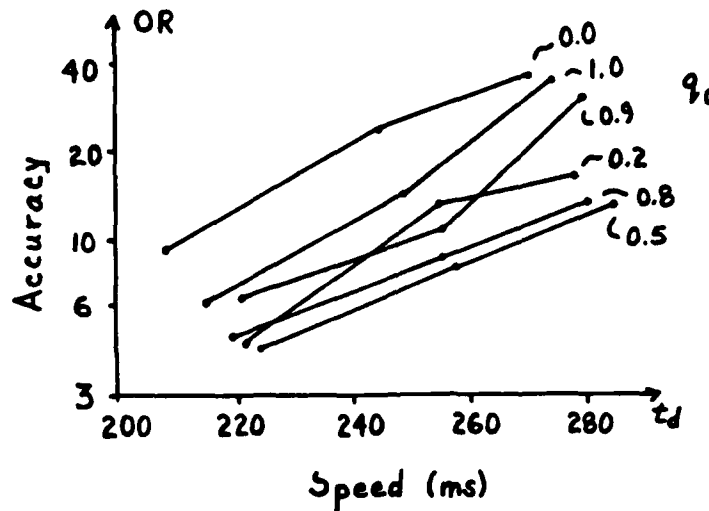


Figure 5.7 Speed/Accuracy Characteristic of Second Member

linear coordinates for operation of the second member under overload conditions. Because different values of q_0 change the processing time requirements, the degree by which a given value of t_d overloads the member changes with q_0 . Thus a family of speed/accuracy curves is shown, which

include data for six q_0 values. Since exclusive use of the vertical threshold requires the least amount of time, accuracy generally remains highest when overload occurs at this operating condition. As q_0 increases, accuracy decreases until required processing time reaches its peak (compare Figures 5.6 and 5.7). Accuracy then improves as q_0 moves further toward 1.0, and as switching overhead diminishes. For further details on how the data shown in the figure were obtained, see Appendix B.

The description of behavior represented by Figure 5.7 will be the basis for the second member's information processing model. Basically, each q_0 locus can be linearized and parameterized by a slope and intercept. Behavior for intermediate values of q_0 can then be obtained by interpolation. Expressing this set of relationships in terms of a input/output mapping can be done as follows. To begin, the overall input/output behavior of the member is essentially that of threshold comparison tests in which errors are made:

$$\bar{k}_2: \text{ if } u = j \text{ and } \begin{cases} y_2 \geq t_{2j} \\ y_2 < t_{2j} \end{cases} \begin{cases} v = 1 \text{ wp } 1-q_2 \\ v = 0 \text{ wp } q_2 \\ v = 1 \text{ wp } q_2 \\ v = 0 \text{ wp } 1-q_2 \end{cases} \quad j = 0,1 \quad (5.23)$$

In words, the member performs the required comparison test correctly with probability $1-q_2$ and makes an error with probability q_2 . Note that these errors are local input/output errors, and may or may not correspond to organization detection errors.

The error rate of the second member depends on the degree to which he is overloaded. Let

$$f = \log(\text{OR}) \quad (5.24)$$

Then

$$q_2 = \frac{1}{1 + e^{f(t_d, q_0)}} = \frac{1}{1 + OR} \quad (5.25)$$

expresses analytically the transformation between accuracy, as measured by the odds ratio, and the input/output error rate. Furthermore, linearization of the observed relationship between f , q_0 , and t_d can be written in the form of

$$f = f(t_d, q_0) = f_s(q_0) \cdot [t_d - t_c(q_0)] \quad (5.26)$$

The quantity f_s represents the slope of the speed/accuracy curve for a given q_0 and the quantity t_c is related to the intercept of the linearized relationship. The latter can be interpreted as the processing time at which chance behavior by the organization member occurs, although this is not its primary function in the model. Both f_s and t_c are estimated from data observed from the second task situation, and the expression in eq.(5.26) is considered to be valid only for a specified range of t_d values, all of which are such that the member is overloaded.

Taken together, eq.(5.23)-(5.26) are the information processing model of the second member. The model depends fundamentally on four parameters: two thresholds (t_{sj}), the deadline assigned (t_d), and the amount of threshold switching (q_0). The deadline to be assigned has already been determined by the time allocation, as discussed previously. Assuming that the member will desire (or can be trained) to operate to minimize input/output errors and assuming operation in an overload state, then the allowed processing time will be used to its fullest extent. This means that $t_d = \tau_s$ in the model. Note that τ_s is determined externally to the member and is subject to variation as the organization's environment changes.

In terms of the general methodology framework, the parameters listed above are classified as

$$\theta_2 = (t_{20}, t_{21}) \quad (5.27)$$

$$\lambda_2 = () \quad (5.28)$$

$$\pi_2 = (q_0) \quad (5.29)$$

$$\omega_2 = (\tau_2) \quad (5.30)$$

Unlike the first member, the thresholds used by the second member do not affect processing time requirements. This is a modeling assumption made on the premise that the thresholds will not take on extreme values such that they are very near a border of the display. That is, so long as there is some uncertainty in where the observation will fall with respect to the threshold, it is assumed that the time required to locate the dot and judge its position with respect to a threshold tends to remain constant.

Finally, there are no information processing parameters in the model, which reflects the fact that the second member has not been given any options in completing his task. However, from the viewpoint of the second member there is a choice made for each observation. It is the selection of which threshold to use, but it is made by the first member. This is reflected in the dependence on π_2 .

5.4 Satisfactory Nominal Design

5.4.1 Integration of Design Elements

The elements of the organization design, which include the analytic organization structure and the implementations of decision rules, have been established. The third phase of design can now begin, which is to integrate these elements to obtain a nominal design, and then to evaluate the design with respect to requirements. For the situation at hand, there are four individual task situation and information processing parameters that must be placed to determine a nominal design. The specific problem to be solved is given as

Problem CNO

$$\begin{aligned} & \text{minimize} && \left\{ J_0(k, \omega^N) = \text{pr}(\text{detection error}) \right\} \\ & t_1, t_{20}, t_{21} \\ & q_1 \\ & \text{s.t. } T_{p1} \cdot (\tau_1)^{-1} \leq 1 \end{aligned}$$

where

$$k = (k_1, k_2) \quad (5.31)$$

and k_i are given by eq.(5.14) and eq.(5.23).

Because of the differences in decision rule implementations, only the first member's workload limit appears as a constraint in the problem formulation. The second member has been placed deliberately in an operating region of overload and thus a constraint that maintains workload within limits is not appropriate. The extent by which processing load exceeds limitations is a factor, however, and appears directly in the member's input/output behavior model.

Consider now the solution to Problem CNO for the case where $\tau_0 = 260$ ms and $\tau_d = 520$ ms, and where the organization members are those whose operating characteristics are shown in Figures 5.4 and 5.7. The values assumed for τ_0 and τ_d imply that

$$\tau_1 = 260 \text{ ms} \quad (5.32)$$

$$\tau_2 = 260 \text{ ms} \quad (5.33)$$

These values are shown in Figure 5.8 superimposed on the respective models of organization members. Note that for the second member, the linearized model developed to represent observed behavior is shown in Figure 5.8.

In the upper part of the figure, the vertical distance between the $\tau_1 = 260$ ms constraint and SCR processing time is proportional to the fraction of fast guessing required. For example, if $t_1 = t_1^*$, then

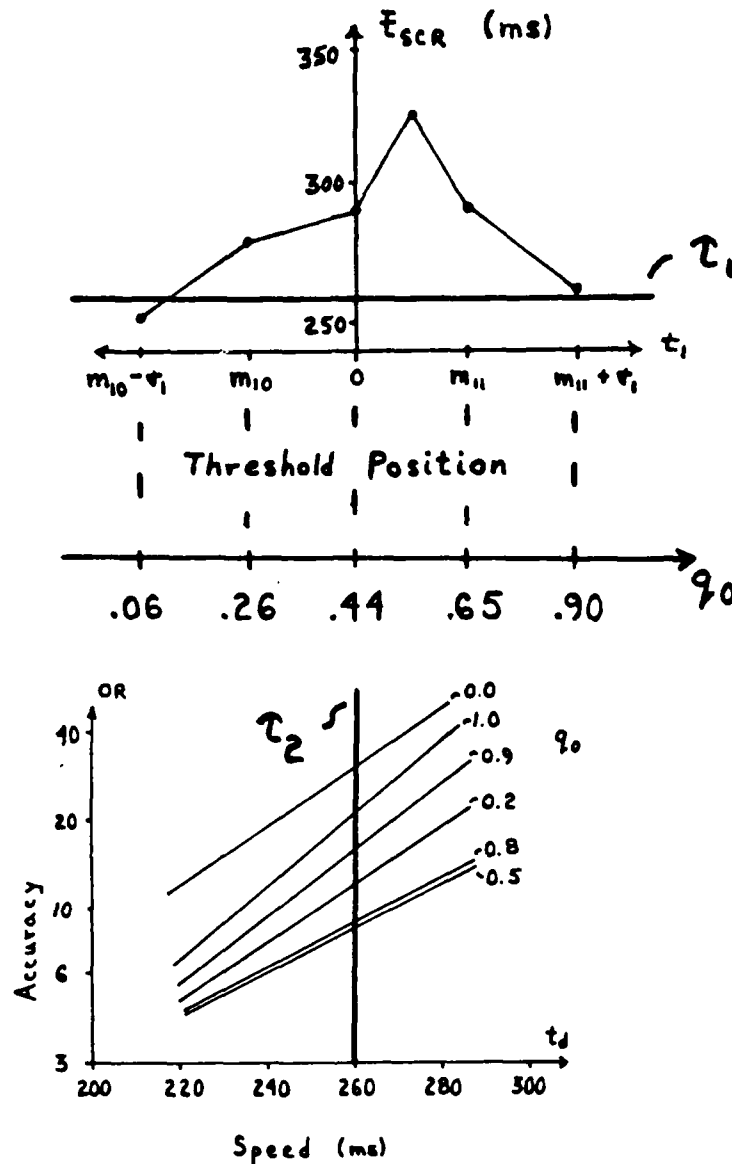


Figure 5.8 Illustration of Solution to Problem CNO

$q_1 \approx 0.27$. If t_1 is at its lower extreme, however, no fast guessing is necessary. For a given bias in fast guessing, placement of t_1 not only establishes q_1 , but it also determines the distribution on u , and consequently the frequency of threshold switching by the second member. Assuming that a 50/50 bias is used when fast guessing, i.e. $g_1 = 0.5$, the correspondence between t_1 and q_0 is shown in the middle of Figure 5.8. As t_1 nears its minimum and maximum values, the amount of switching decreases. In the former case, the vertically displayed threshold (t_{11})

is used more frequently; in the latter case it is the horizontally displayed threshold (t_{10}) that gets more use. Thus the value of t_1 selected, through its effect on q_0 , determines which speed/accuracy locus the second member will operate on. The value of τ_2 then determines which point on this locus is the actual operating point. Finally, though not shown explicitly in Figure 5.8, the thresholds t_{1j} are a factor in the solution of Problem CNO since they have an effect on organization performance.

In solving Problem CNO for the present design situation, a basic tradeoff must be made in the optimization. At one extreme is the option to retain the first member's ideal threshold t_1^* , which gives "high quality" indications, but cannot be used all the time. If this option is chosen, the second member uses his thresholds with nearly equal frequency, which in turn places his operation at a lower level of input/output accuracy. At the other extreme is the option to place t_1 at its minimum value so that no fast guessing is required, but also so that all indications u made by the first member are of lower quality. This option places the second member at a higher accuracy level, however. Of course, there exist many other solution possibilities that represent a compromise between the two extremes.

The solution to Problem CNO for the particular organization in Figure 5.8 places t_1 at its minimum value. Thus no fast guessing is required in the nominal organization design. In addition, the second member's thresholds are adjusted away from t_{1j}^* . Details of the solution for this particular organization are given in Appendix B. The solution is such that the accuracy of the second member is maximized. Evidently, since this member has the "last word" on the organization's detection decision, it is desirable that it should be made in consonance with the observation presented, rather than directly opposed to it. Furthermore, it is worth compromising the quality of the first member's indication to do this. Partial compensation for this loss is made by adjusting t_{1j} , however. Finally, though the solution to Problem CNO for the set of parameter values illustrated above represents the selection of an extreme option,

this need not always be the case. Appendix A contains a general discussion of solution characteristics.

5.4.2 Evaluation of Nominal Design

Two criteria were established in Phase I for the organization design. The first was that the detection error rate of the organization be less than 15%, i.e. $J_0 < \bar{J}_0 = 0.15$. The detection error rate for the nominal organization obtained above has $J_0 = 0.12$. Thus it meets the performance design goal, at least nominally.

A second criterion for the design is that it must be tolerant to variations in the rate of observation (τ_0) and the maximum delay in detection response (τ_d). As a preliminary indication whether this criterion is met, assume that the thresholds are fixed at their nominal values, and consider if the organization would continue to operate at all should τ_0 and τ_d vary from their nominal values. If τ_0 were to decrease, there would be an immediate impact on the first member, since τ_1 would decrease. Nominally, there is no fast guessing required by the first member. However, decreases in τ_1 would mean that $\bar{t}_{SCR}(t_1^c) > \tau_1$, but since the member has the option to fast guess, he can compensate by exercising that option so that T_{p1} remains less than or equal to τ_1 . Thus, assuming that the transition to a new operating point is smooth, the organization remains tolerant to a decrease in τ_0 .

Changes in the maximum delay in detection decision (t_d) are presumed to primarily affect the second member. One possible scenario that motivates this viewpoint is the situation where the organization forwards its detection decision to an outside destination. A request by this destination for a faster response has an immediate impact on the second member. To meet the request, the second member can establish a faster deadline for his response. As with the first member's adaptation to changes in τ_0 , the ability of the second member to make a smooth transition to a new operating point is not addressed in the current

information processing description. However, it is true that operating points corresponding to lower values of τ_2 are possible. Assuming that a smooth transition can take place, a decrease in τ_2 will simply move the second member to a lower point on the q_0 speed/accuracy locus that he is operating on.

The discussion above indicates that the nominal design is tolerant to changes in τ_0 and τ_d , at least in the sense that the organization will keep operating should such changes occur. Whether the detection error rate remains within design goals is not clear, however. A worst case test of the design is where τ_1 and τ_2 are reduced simultaneously. Suppose that τ_0 and τ_d change so that τ_1 and τ_2 are reduced by 5%. Leaving the thresholds fixed at their nominal values and assuming that each member can make his respective adaptation to a new operating point, the detection error rate for the organization at the new operating point is 0.14. Since it is within the limit \bar{J}_0 , the nominal organization design can be declared satisfactory with respect to design goals.

Though the nominal design that has been developed is satisfactory, the fact that the first member's operation is at an extreme point of the region for which a valid information processing model has been developed could merit further consideration in evaluating the design. Based on the nominal design outcome, the designer might conclude that a good match has not been realized between the member's job description and the task situation developed to do the job. In the present case, the designer might want to reconsider whether the first member's task situation can be revised so that using a higher quality threshold becomes part of the nominal design. This could be done, for example, by attempting to reduce the processing time required for the first member's threshold comparison test, say through modifying the observation display. The possibility of revising the organization design to achieve better balance between organization members will not be pursued further here, however. The purpose in raising the issue is to point out that even though a nominal design might satisfy design goals, it may still be declared marginal and in need of improvement.

5.5 Test of Organization Design

Once a satisfactory nominal organization design has been obtained, the design process terminates as far as the methodology described in this thesis is concerned. At this point, the organization structure is presumably ready for advanced stages of development, such as prototype building. Such a presumption is, of course, based on the validity of the methodology. That is, execution of each methodology phase, particularly the integration of design elements, is assumed to represent a viable and legitimate step in the design process so that the resulting nominal design is representative of what will be observed if the organization is actually built. That the methodology is viable in this respect remains to be established, however, since no organization structure has been previously built and put into operation using this approach explicitly. This section pursues such an end. The nominal organization obtained for the detection task is operated as designed, and its behavior is observed and compared with that predicted by the methodology. In addition, the organization is also operated under several other conditions as a further test of the validity of the design approach.

Nominal Organization Operation

There are several characteristics of the nominal design obtained for the detection task that suggest hypotheses about organization operation. First, if t_1 is set to its minimum value as per the design, there should be little fast guessing observed as the first member executes his task. Second, the design predicts a certain level of input/output accuracy for the second member. Both of these predictions represent operation of organization members in regions that were examined in the development of their respective information processing models. Thus the hypotheses are fundamentally tests of individual model validity, and therefore serve as a useful check on the work completed in Phase II of the design process.

A more interesting hypothesis about organization operation is the level of performance that will be realized. Organization detection error is a quantity that characterizes the organization as a whole; it cannot be inferred or assessed by individual members. Since detection error was the criterion used in Phase III to discriminate between possible nominal design solutions, predicted organization performance is truly a prediction made using the methodology. The extent to which actual performance of the organization matches that which is predicted represents a key test for the applicability of the design approach. In subsequent discussion, operation of the organization at its nominal design point will be designated as Test Condition 1.

Alternative Modes of Organization Operation

Besides selecting a particular nominal operating point and thereby predicting behavior of the organization, the integration phase of the methodology must also in effect predict behavior at many other potential design solutions in order to discriminate among them. One of the potential solutions of particular interest is the one that leaves the thresholds of both members unchanged from their respective decision rule values as determined in Phase I. In the present design situation (see Figure 5.8), this would result in a fast guessing level of $q_1 \approx 0.30$. Furthermore, q_0 would be near 0.50 and the input/output accuracy of the second member would be lower than that of the nominal design. The detection error rate at this operating point is also predicted to be higher: $J_0 = 0.17$. That is, with $t_1 = t_1^*$, $t_{2j} = t_{2j}^*$, and $q_1 = 0.30$, the organization detection error rate will be approximately 35% higher than at the nominal design point. This is a testable hypothesis regarding the organization's operation and is designated as Test Condition 3. Note that it predicts qualitatively different behavior than at the nominal design operating point.

Thus far it has been assumed that the first member fast guesses with a 50/50 bias ($g_1 = 0.5$). If this bias is other than 50/50, a slightly different set of predictions about organization behavior is obtained. In

particular, suppose that the first member indicates the most likely value of H when fast guessing. This means that $g_1 = 0$, i.e. the member says $u = 1$ when guessing. With $t_1 = t_1^*$, the fraction of fast guessing is about 0.30, which is the same as for Test Condition 3. The corresponding value of q_0 is not the same, however. Because of the fast guessing bias and the significant amount of FG responses, it is much more likely that the first member will respond with $u = 1$. In fact, q_0 decreases to about 0.20. This in turn operates the second member on an accuracy level that is somewhere between that of the Test Conditions 1 and 3. Organization detection error for this intermediate test condition, designated as Test Condition 2, is also predicted to be between that of the other two conditions. For $g_1 = 0.0$, and with thresholds set at their ideal values, predicted detection error is $J_0 = 0.15$.

The foregoing has established three different test conditions for the organization, each of which predicts a slightly different operating behavior. They are summarized in Table 5.1. Additional discussion

Table 5.1 Predicted Organization Behavior

#	Test Condition		q_1	q_0	q_2	J_0
	Thresholds	FG bias (g_1)				
1	Nominal Design	0.5	0	0.06	0.048	.12
2	Normative	0.0	0.27	0.31	0.083	.15
3	Normative	0.5	0.27	0.44	0.098	.17

regarding how these values were obtained is found in Appendix B, and discussion of a more general nature regarding the effect of bias on organization operation is contained in Appendix A. With respect to the latter consideration, it happens that the nominal design solution for the present situation remains the same no matter what the guessing bias. Thus Test Condition 1 in Table 5.1 represents the lowest detection error achievable using the present organization design elements.

Test Results

To test the predictions made about organization behavior, the organization was operated at the conditions given in Table 5.1. A key feature of the experimental setup was the implementation of alternative fast guessing biases. To accomplish this, when the first member elected to fast guess he was instructed to depress both mechanical buttons. In this way, it was obvious to the experimenter when the fast guess option was selected and an unambiguous estimate of q_1 could be made. Furthermore, each double-button push could be assigned a value of u according to the bias desired, and then be forwarded to the second member. Further details regarding the experimental set-up used to test the organization are given in Appendix B.

Organization behavior observed at the three conditions tested is summarized in Table 5.2. Comparison between Table 5.1 and Table 5.2

Table 5.2 Observed Organization Behavior

Test Condition						
#	Thresholds	FG bias (g_1)	q_1	q_0	q_2	J_0
1	Nominal Design	0.5	0.0	0.04	0.067	.13
2	Normative	0.0	0.35	0.27	0.078	.14
3	Normative	0.5	0.35	0.44	0.104	.16

indicates substantial agreement between predictions and observations. In particular, there was no fast guessing required at the nominal design operating point, but a significant amount was required when t_1 was left at t_1^* . The predicted relative differences in q_0 values have been realized and the input/output error rate of the second member was observed to vary accordingly. Thus the information processing models of each member appear to be reliable as design elements.

The integration of design elements has also given reasonably reliable

predictions of organization behavior. The absolute detection error rates observed for the test conditions are close to those predicted. More importantly, however, is that the relative ordering on these results is in agreement with that predicted. The nominal design has yielded the lowest detection error and the effect of fast guessing bias has distinguished between Conditions 2 and 3 as predicted. Given the results obtained, it appears that the models developed, and their integration using the methodology, have captured reasonably well the first order effects within the organization and thus provide a sound basis for organization design.

The agreement between Tables 5.1 and 5.2 does not represent an isolated set of coincidences. Appendix B documents the development and testing of five other organizations that have the same basic design form, but have different individuals as members. Operation of these organizations at the same test conditions produces results similar to those reported in this chapter. These results add further evidence in support of the methodology as a viable approach to organization design.

Two specific conclusions are evident from the test results. One is that failure to take human limitations into account can result in performance that is considerably different from that which assumes ideal human behavior. Recall that the organization detection error rate for the analytic organization structure is 0.06. This is substantially less than that predicted and obtained in either Condition 2 or 3. A second conclusion is directly related to the first: there may be considerable advantage to adjusting organization parameters when organization members are affected by workload limitations. This is evident by comparing the results for Condition 1 with those for Conditions 2 and 3.

5.6 Chapter Summary

In order to demonstrate in a concrete way the approach to organization design advanced in the thesis, this chapter has executed the design methodology from beginning to end. The result has been the

development of a two-member organization that makes a minimum error detection decision as to the presence or absence of a target. Each member has been provided with a particular task to accomplish, which has been specified not only with regard to overall organization performance, but also with due consideration for the workload limitations that characterize each member.

Once a satisfactory nominal design was obtained, several test conditions were selected based on the behavior predicted for the organization. The organization was then operated under these conditions in a laboratory setting, and substantial agreement between predicted and actual behavior was observed. As such, these results constitute an existence proof: there is at least one realistic human team decision-making problem that can be solved using the blend of analytic human modeling and empirical human factors data that forms the basis of the methodology described herein.

VI. SUMMARY AND SUGGESTIONS FOR FUTURE WORK

6.1 Summary

This thesis has considered the problem of analysis and design of human information processing organizations. The main focus has been on how and at what point in the analysis to include consideration of human characteristics and limitations. An approach has been suggested for structuring the problem so that a balance is struck between the complexities of considering how human behavior impacts all aspects of the organization, and the hazards of neglecting consideration of human limitations in order to simplify the problem. Specifically, an approach has been suggested that incorporates both top-down and bottom-up phases, but which also includes an integration phase that guarantees that the first two phases converge.

The top-down phase is concerned with analytically structuring the organization's task. Organization topology, input and output message sets for individual members, and relevant features of the organization's environment are considered and modeled in this phase. In addition, performance goals for the organization task are formulated as an optimization objective function. Then, the functional relationship between inputs and outputs for each organization member is treated as a variable and organization performance is optimized over the possible input/output mappings. The result is a set of decision rules that represent ideal information processing behavior by organization members, but which have not necessarily taken into account human processing limitations.

The bottom-up phase uses the decision rules of members to structure their respective tasks in specific physical and mental terms. That is, a task situation is devised as the collection and arrangement of equipment for accomplishing the information processing represented by the decision rule. In addition, an information processing model is developed that

describes actual human behavior at the task, which includes a characterization of input/output behavior and induced workload. Both of these descriptions are developed in terms of task situation and information processing parameters, which usually occurs through empirical means.

Finally, a third design phase integrates the top-down and bottom-up phases. A second optimization problem is solved to do this. The input/output descriptions of actual behavior are substituted for the decision rules, and workload descriptions are added as constraints. Organization performance is then re-optimized over task situation and information processing parameters. The result is a nominal design that specifies how task situation parameters should be set in order to fix organization structure, and also how individual members should exercise their processing options.

The key advantage of the design approach is that the separation into normative and descriptive phases simplifies the problem without greatly limiting design options. Indeed, by deriving job descriptions for individual members at an intermediate design stage, the designer is provided with a focus for completing subsequent design steps. A second advantage is that tradeoffs between member workload and organization performance are made apparent in the third design phase. At this point in the design the organization structure is complete, and potential tradeoffs are viewed and evaluated in terms of parameters that relate to individual members.

The three-phase approach has been stated as a set of steps that form a methodology for design, and the thesis has argued for the approach in terms of this methodology. The argument has proceeded on several levels. First, the considerations that are intended for each design step have been discussed on a conceptual level. Second, on a more concrete level, the methodology has been discussed in terms of specific classes of analytic organization structures and information processing model structures. Third, an example drawn from these classes has been constructed

conceptually using the methodology.

Besides making a case for the design approach through discussion and argument, an existence proof has been offered for the applicability of the methodology. A complete organization has been designed and tested by executing each of the methodology steps in turn. The test results have indicated that the organization operates as predicted. This is particularly supportive of the integrative aspects of the methodology. That is, the normative and descriptive design phases in many respects represent familiar problems for systems analysts and those who model human behavior, respectively. The most novel feature of the methodology is the integration of the two. The extent to which the integration represents a successful design step provides support for the overall design approach. The results of the organization design completed in this thesis offer such support. In addition to successfully predicting characteristics of organization operation, it has been demonstrated in terms of this specific design that neglecting human limitations in the design process can produce behavior that is significantly different than "ideal". Furthermore, it has been shown that by adjusting parameters within a given design structure there can result a significant improvement in organization operation.

6.2 Suggestions for Future Work

Given that the thesis is essentially an argument for a particular approach to human information processing organization design, one obvious direction of future work is to further test the range of application of this approach. One organization exists that attests to the methodology's utility. It would be of interest to apply the approach to other design situations, and thereby gain further experience in its use as a design tool.

A second direction for further work is one that presumes the methodology to be a reasonable approach and takes as point of departure

the "job description" feature of the methodology. Recall that the job description in the form of a decision rule is the key link between the normative and descriptive design phases. With respect to the descriptive phase, it would be of great benefit if decision rules were a reasonable match with human capabilities, and could therefore be readily translated into task situations and information processing models. Such an outcome would be facilitated by formulating the analytic organization structure with a view toward eventual human execution of information processing tasks. Incorporating such a view in the analysis of large-scale and distributed decisionmaking problems may lead to alternate formulations of these problems.

A counterpart to the above suggestion exists. As discussed earlier in Chapter 3, the job description provides a focus for the designer in specifying a task situation. The designer essentially attempts to match a given decision rule to an information processing model for a task situation. Much work has been done previously on modeling human behavior in various situations. To take advantage of this work in the present context, a classification of the models developed according to input/output behavior would be of benefit to the organization designer as he seeks to match decision rules with task situations. The suggestion here is that a catalog might be developed, over whose entries the designer can search to find one that suits his particular needs.

Two final suggestions pertain primarily to the analytic aspects of the design process. The first is related to the translation of a statement of design objectives for a given organization task into an organization structure. Issues such as how to decide the number of organization members and how to set their topological interconnection are included in this consideration. Additional investigation is needed to clarify these issues and to advance approaches for addressing them. A second suggestion relates to the solution of the first optimization problem within the design methodology, Problem DR. As noted in Chapter 2, there are at present only a few classes of analytic organization structures for which solutions and solution techniques for decision rules

are known. In the present context, additional work is needed to enlarge this number, since by doing so the range of application of the design approach will also be enlarged.

APPENDIX A

Distributed Decisionmaking with Constrained Decision Makers A Case Study

A.1 Introduction

A main goal in most distributed decisionmaking formulations, particularly team theoretic ones, is to obtain normative decision rules that represent the desired behavior of each decision agent or team member [4]. This appendix considers a modified team theoretic problem that incorporates decision rules that are descriptive of actual human behavior, and furthermore takes into account the processing load incurred to execute these decision rules. When models for actual human behavior are substituted for the normative decision rules in the team structure, team behavior in general changes. Furthermore, the workload of team members may be such that desired team operation exceeds human processing limitations. Thus, given the basic team structure, a problem can be formulated to choose decision rules, to be realized by actual human behavior for best team performance, subject to their feasibility with respect to team member processing load.

The problem considered is motivated by the specific organization design developed in Chapter 5. The same analytic organization structure is common to both, but the models of human behavior considered here represents generalized and idealized versions of those used in Chapter 5. Thus while the analytic results obtained are of interest in the context of a modified team problem, they are also useful in supporting the design effort in Chapter 5. In particular, knowing the general characteristics of the solution to the problem investigated in this appendix enables the designer in Chapter 5 to formulate predictions about organization performance and individual member behavior in various operating regions.

The specific team structure considered is that of a two-member,

tandem distributed detection network. The next section describes this structure and reviews the characteristics of theoretical team member behavior. A key feature of the decision rules is the presence of thresholds, which each member uses to make comparison tests. A model for the information processing required to execute such a test is then described, with processing time used as the measure of workload.

The complete model for each member's actual behavior includes a second element, however, which accounts for behavior when processing time for threshold tests exceeds the time allowed. This element derives from human ability to trade accuracy for speed. Two different mechanisms for doing this are incorporated, one for each member. The overall actual behavior and processing load realized is parameterized by the thresholds used and other parameters that derive from the speed/accuracy tradeoff capability. The modified team theoretic problem is then to place these parameters for minimum team error.

The third section discusses the characteristics of the problem solution. A particular consideration of interest is whether, and if so under what conditions, it remains desirable to retain the thresholds obtained in the original (unconstrained) team problem. Section four investigates a special case of the problem, from which principles of general interest are apparent. Finally, section five summarizes the appendix.

A.2 Problem Formulation

A.2.1 Team Structure

Consider the two-member, tandem, distributed detection network shown in Figure A.1. Each team member receives a conditionally independent, gaussian observation on the presence or absence of a given phenomenon H . Based on his observation, the first member selects one of two symbols to send to the second member. The latter then incorporates his own measurement with the received symbol to make a detection decision for the

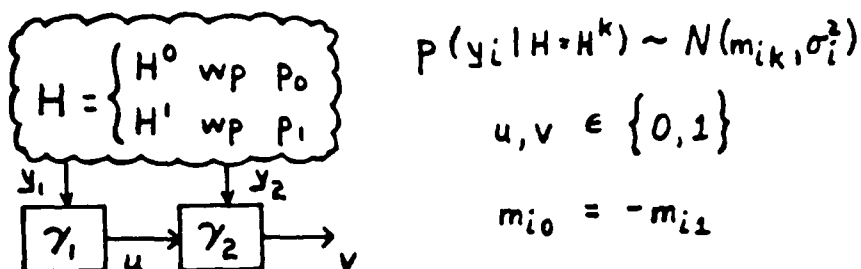


Figure A.1 Team Structure

network. The decision rules γ_i^* for each team member that minimize the probability of error in detection are known [7]. They are threshold tests as given in (A.1).

$$\begin{array}{ll} \gamma_1^* : & \gamma_2^* : \\ & \text{if } u = j \quad (j = 0, 1) \quad \text{and} \\ \left\{ \begin{array}{l} \text{if } y_1 \geq t_1^* \quad u = 1 \\ \text{if } y_1 < t_1^* \quad u = 0 \end{array} \right. & \left\{ \begin{array}{l} \text{if } y_2 \geq t_{2j}^* \quad v = 1 \\ \text{if } y_2 < t_{2j}^* \quad v = 0 \end{array} \right. \end{array} \quad (\text{A.1})$$

Basically, the first member biases the second member's choice by selecting the latter's threshold.

A.2.2 Information Processing Models

Now consider that the threshold comparison tests in (A.1) are to be accomplished by humans. For example, the observation could be displayed visually as a horizontally displaced dot, with the threshold also displayed as a vertical line displaced according to its value (see Chapter 5 and Appendix B). Viewing such a display and selecting a response takes time. Furthermore, threshold position with respect to the likely position of observations will have an effect on the time required to select a response. In particular, assume that a comparison with threshold t requires, on the average, \bar{t}_p seconds to make, where

$$\bar{t}_p = \bar{t}_p(t) = a - b \cdot (t)^2 \quad a > 0, b \geq 0 \quad (\text{A.2})$$

Given that observations are predominantly near zero, the model in (A.2) reflects the observed behavior that response time decreases as the uncertainty decreases in the response required. In eq.(A.2), as t becomes large in absolute value ($b \neq 0$), the likelihood that observations will fall only on one side of t is high.

First Team Member

The first team member performs his task using a single threshold. The processing time required to do this test is given by eq.(A.2); specifically, it is $\bar{t}_{p11}(t_1) = a_1 - b_1 \cdot (t_1)^2$. In addition, it is assumed that the input/output behavior realized is such that a flawless comparison can be made. Denote by \bar{k}_{11} the probability distribution $p(u|y_1)$ that characterizes the realized input/output behavior. The model is then that of

$$\bar{k}_{11} : \begin{cases} \text{if } y_1 \geq t_1 & u = 1 \text{ wp } 1 \\ \text{else} & u = 0 \text{ wp } 1 \end{cases} \quad (\text{A.3})$$

Suppose now that the operation of the team is such that the member must complete comparison tests at the rate of one every τ_1 time units. If it happens that t_1 is set such that $\bar{t}_{p11}(t_1) > \tau_1$, the member will be overloaded. An alternative processing mode is therefore provided, which is the option to "guess." This means that the member ignores the observation y_1 and responds arbitrarily according to some guessing bias g_1 . Input/output behavior when guessing is modeled by the distribution \bar{k}_{12} , where

$$\bar{k}_{12} : \begin{cases} u = 0 & \text{wp } g_1 \\ u = 1 & \text{wp } 1 - g_1 \end{cases} \quad (\text{A.4})$$

To make this a viable option, assume that the time required to exercise it, denoted by \bar{t}_{p12} , is less than $\bar{t}_{p11}(t_1)$ for some range of t_1 values.

Finally, because the team member has two options, there will be an additional amount of processing time required to switch between them. Switching overhead depends on switching frequency. A model for this is given by the expression

$$d_1 \cdot (1 - q_1) \cdot q_1 \quad (\text{A.5})$$

which is illustrated in Figure A.2. In eq.(A.5), q_1 is the fraction of

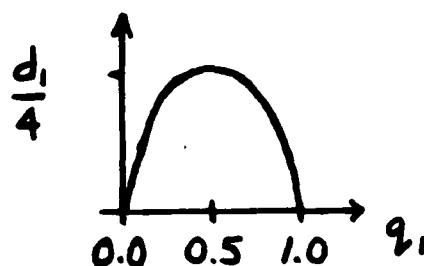


Figure A.2 Processing Time Overhead for Switching

guessing and d_1 is a scale factor. The model for switching is such that if one option is used exclusively, (A.5) is zero. Switching overhead is maximum when each option is used with equal frequency ($q_1 = 0.5$). Thus, the first team member has an input/output behavior modeled by \bar{k}_1 that requires an average processing time of T_{p1} :

$$\bar{k}_1 = (1 - q_1) \cdot \bar{k}_{11} + q_1 \cdot \bar{k}_{12} \quad (\text{A.6})$$

$$T_{p1} = (1 - q_1) \cdot \bar{t}_{p11}(t_1) + q_1 \cdot \bar{t}_{p12} + d_1 \cdot (1 - q_1) \cdot q_1 \quad (\text{A.7})$$

The model given in eq.(A.6) and eq.(A.7) is basically the so-called Fast-Guess model [28], which reflects one mechanism whereby humans can trade speed for accuracy.

Second Team Member

The second team member switches between two thresholds. Assuming an overhead for switching similar to (A.5), the average time required to accomplish this task depends on the threshold values, and the relative frequency of using them:

$$T_{p2} = \sum_{j=0}^1 \left[p(u=j) \cdot (a_{2j} - b_{2j} \cdot (t_{2j})^2) \right] + d_2 \cdot p(u=0) \cdot p(u=1) \quad (A.8)$$

As with the first team member, it assumed that the second member is subject to a processing time limit; in this case it is assumed to be a deadline constraint τ_2 . So long as $T_{p2} \leq \tau_2$, the team member can accomplish this processing without error. Errors will be made, however, if $p(u)$, t_{20} , and t_{21} are such that $T_{p2} > \tau_2$. The likelihood of errors depends on the difference between the deadline imposed, denoted t_d , and the processing time required (T_{p2}). Thus the input/output behavior of the second member, \bar{k}_2 , is as follows:

$$\bar{k}_2: \text{ if } u = j \text{ and } \begin{cases} y_2 \geq t_{2j} \\ y_2 < t_{2j} \end{cases} \begin{cases} v = 1 \text{ wp } 1-q_2 \\ v = 0 \text{ wp } q_2 \\ v = 1 \text{ wp } q_2 \\ v = 0 \text{ wp } 1-q_2 \end{cases} \quad (A.9)$$

In words, the second member performs the threshold comparison test correctly a fraction $1-q_2$ of the time, and makes an error on the fraction q_2 of the observations processed.

The specific model for the error fraction q_2 is given by

$$q_2 = \frac{1}{1 + e^f} \quad (A.10)$$

where

$$f = \log\left(\frac{1-q_2}{q_2}\right) = \begin{cases} f_s \cdot (t_d - T_{p2}) + f_m & , T_{p2} \geq t_d \\ f_m & , T_{p2} < t_d \end{cases} \quad (A.11)$$

Eq.(A.11) is derived from Pew [29], who has suggested that if accuracy is measured using the "odds ratio" $(1-q_2)/q_2$, then the human speed/accuracy tradeoff can be represented as a log-linear relationship between accuracy and processing time. The relationship has been realized in eq.(A.11). For analytical convenience, however, it is assumed that accuracy has an

upper limit, i.e.

$$f \leq f_m < \infty \quad (A.12)$$

which effectively means that q_2 is non-zero. The model represented by eq.(A.11) is illustrated in Figure A.3. To understand the relationship

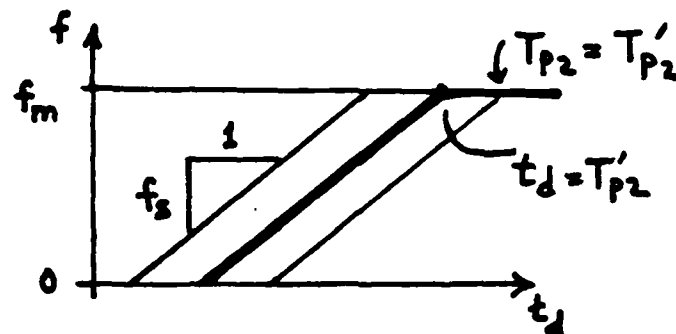


Figure A.3 Speed/Accuracy Model of Second Team Member

between f , t_d , and T_{p2} , consider a particular value of T_{p2} , say T_{p2}' . Recall that T_{p2} is the amount of time required to do the task without overload, or in the present context, at maximum accuracy. So long as $t_d \leq T_{p2}'$, maximum accuracy is possible, and operation on the $f = f_m$ line occurs as shown in Figure A.3. However, when the deadline t_d decreases below T_{p2}' , there is insufficient time to do the task and still retain maximum accuracy in processing. The degree by which accuracy decreases for decreasing t_d is governed by the parameter f_s , which is the slope of the speed/accuracy loci in Figure A.3.

A.2.3 Problem Statement

Five independent variables have been specified within the team member models. They include the three comparison thresholds (t_1, t_{s0}, t_{s1}), the amount of guessing by the first member (q_1), and the processing time deadline for the second member (t_d). Substituting k_1 for γ_1^* and adding the processing time constraints for each member, a constrained

optimization problem can be formulated to minimize the detection error probability for the team, subject to meeting the processing time limitations of each member. Denote by J_0 the detection error probability of the team. Then, formally stated, the problem is as follows.

Problem A1 (Constrained Optimization Problem)

$$\begin{array}{ll} \min_{t_1, t_{20}, t_{21}, q_1, t_d} & \left\{ J_0(q_1, t_1, t_{20}, t_{21}, t_d) \right\} \\ \text{s.t.} & T_{p1} \leq \tau_1 ; \quad t_d \leq \tau_2 \end{array}$$

A.3 Solution Characteristics

There are several issues of interest with respect to the solution of Problem A1. One is whether it is ever to any advantage to set the deadline t_d for the second member to be strictly less than τ_1 . This is shown not to be the case, due to the monotonicity of q_2 in t_d . A second issue is whether a possible solution is to leave the thresholds at their unconstrained optimal values, i.e. t_{10}^* , t_{11}^* , and to tolerate any consequent input/output errors (q_2) or guessing (q_1). At the other extreme is the possible solution of adjusting thresholds such that q_1 and q_2 are minimized. The basic consideration is one of whether it is better to absorb guesses and input/output errors some of the time in order to use quality thresholds most of the time, or to use an "inferior" set of thresholds all of the time. In Problem A1, so long as the thresholds t_{10}, t_{11} affect processing time of the second member, it is better to adjust them. Solutions to Problem A1 do not necessarily minimize q_2 and q_1 , however.

A.3.1 Reformulation of Problem A1

Examination of Problem A1 is greatly facilitated by taking advantage

of the fact that the joint distribution $p(u, H)$ completely characterizes the analytical link between team members [7]. Thus the minimization in Problem A1 can proceed in two stages. First, t_{10} , t_{11} and t_d can be placed as a function of $p(u, H)$. Then, since there is a 1-1 relationship between (q_1, t_1) pairs and $p(u, H)$ distributions, a second minimization can be performed over these distributions to place q_1 and t_1 , thereby solving Problem A1.

Denote by p_{jk} the quantity $p(u=j, H=H^k)$. Then it is convenient to represent the distribution $p(u, H)$ as a vector \bar{P} , where

$$\bar{P} = [p_{00}, p_{10}, p_{01}, p_{11}]' \quad (A.12)$$

Furthermore, possible \bar{P} values depend on t_1 and q_1 according to

$$\begin{aligned} \bar{P} = & (1-q_1) \cdot [p_{00t}(t_1), p_{01}-p_{00t}(t_1), p_{11}-p_{11t}(t_1), p_{11}]' \\ & + q_1 \cdot [(1-g_1) \cdot p_0, g_1 \cdot p_0, (1-g_1) \cdot p_1, g_1 \cdot p_1]' \\ \triangleq & \bar{P}(t_1, q_1) \end{aligned} \quad (A.13)$$

where

$$p_{00t}(t_1) = \Phi\left(\frac{t_1 - m_{10}}{\sigma_1}\right) \cdot p_0 \quad (A.14a)$$

$$p_{11t}(t_1) = \left[1 - \Phi\left(\frac{t_1 - m_{11}}{\sigma_1}\right) \right] \cdot p_1 \quad (A.14b)$$

and $\Phi(\cdot)$ is the unit normal cumulative distribution function. From eq.(A.13) it is evident that \bar{P} is determined as a combination of two \bar{P} vectors, one corresponding to exclusive use of the threshold t_1 and one corresponding to exclusive use of guessing.

The analysis of Problem A1 is also aided by rewriting the team detection error probability J_0 so that its basic structure is evident. One element of this structure is the team detection error probability when $q_1 = 0$. This is given as the quantity J , where

$$\begin{aligned}
J(\bar{P}, t_{20}, t_{21}) = & \\
& p_{00} \cdot \left[1 - \Phi \left(\frac{t_{20} - m_{20}}{\sigma_2} \right) \right] + p_{01} \cdot \left[\Phi \left(\frac{t_{20} - m_{21}}{\sigma_2} \right) \right] \\
& + p_{10} \cdot \left[1 - \Phi \left(\frac{t_{21} - m_{20}}{\sigma_2} \right) \right] + p_{11} \cdot \left[\Phi \left(\frac{t_{21} - m_{21}}{\sigma_2} \right) \right]
\end{aligned} \tag{A.15}$$

The second element of structure is the input/output error fraction of the second member, q_2 . Incorporating this element gives an overall detection error probability of

$$\begin{aligned}
J_o &= J(\bar{P}, t_{20}, t_{21}) \cdot (1 - q_2(T_{p2}, t_d)) + (1 - J(\bar{P}, t_{20}, t_{21})) \cdot q_2(T_{p2}, t_d) \\
&= (1 - 2J) \cdot q_2 + J
\end{aligned} \tag{A.16}$$

Using eq.(A.16) and the stagewise decomposition described earlier, the approach to solution of Problem A1 is illustrated in Figure A.4.

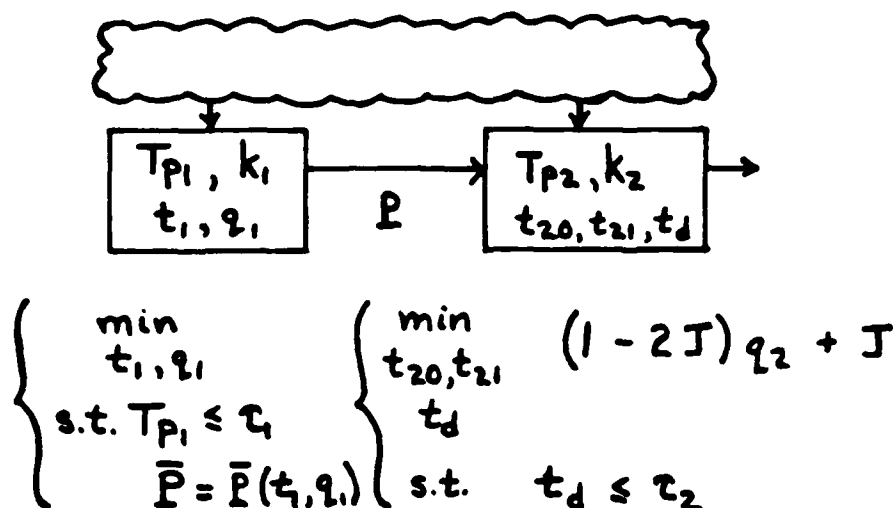


Figure A.4 Illustration of Stagewise Decomposition of Problem A1

Before proceeding to an analysis of solution characteristics, however, it is convenient to formulate a modified version of Problem A1.

Because explicit dependence on thresholds t_{20} and t_{21} occurs in only in the function J and in the determination of processing time T_{p2} , it is possible to aggregate these thresholds into the single variable \bar{T}_{p2} and to substitute a new function \bar{J} for J , where

$$\bar{J}(\bar{P}, \bar{T}_{p2}) = \min_{t_{20}, t_{21}} \left\{ J(\bar{P}, t_{20}, t_{21}) \right\} \quad (A.16)$$

$$\text{s.t.} \quad T_{p2} = \bar{T}_{p2}$$

If \bar{P} is given, then $p(u)$ is known and T_{p2} depends only on the thresholds t_{20} and t_{21} . Furthermore, if T_{p2} is constrained to be constant at \bar{T}_{p2} , then the model of eq.(A.8) specifies that t_{20} and t_{21} determine an ellipse. Eq.(A.16) is therefore a search for the (t_{20}, t_{21}) pair on a specific ellipse that minimizes J . Because J is bounded, such a minimum will exist. Thus there is at least one pair of thresholds $(\bar{t}_{20}, \bar{t}_{21})$ that solve (A.16) for each possible \bar{T}_{p2} value. Multiple solutions to (A.16) are possible, but their existence is not a factor given the problem reformulation in terms of \bar{T}_{p2} . Using this aggregation, Problem A1 can be stated in terms of q_1 , t_1 , \bar{T}_{p2} and t_d as:

Problem A2

$$\min_{q_1, t_1} \left\{ \min_{t_d, \bar{T}_{p2}} \left\{ [1 - 2 \cdot \bar{J}(\bar{P}, \bar{T}_{p2})] \cdot q_2(\bar{T}_{p2}, t_d) + \bar{J}(\bar{P}, \bar{T}_{p2}) \right\} \right\}$$

$$\text{s.t.} \quad T_{p1} \leq \tau_1 \quad ; \quad t_d \leq \tau_2$$

$$\bar{P} = \bar{P}(t_1, q_1)$$

As a technical matter, note that \bar{T}_{p2} is subject to a maximum value that depends on \bar{P} . This maximum occurs where $t_{20} = t_{21} = 0$. In the determination of Problem A2 solution characteristics, this limit is not a factor, however, unless it happens that the unconstrained optimal thresholds t_{2j}^* are both zero for a given \bar{P} value. This is an uninteresting case since it means that the first member's indication is being disregarded entirely.

A.3.2 Second Member Solution Characteristics

Assigning Deadline

Consider now the inner minimization in Problem A2. For given \bar{T}_{p_2} , necessary conditions for a solution value of t_d [30] are given by

$$\frac{\partial \bar{J}}{\partial t_d} \cdot [1 - 2 \cdot q_2] + \frac{\partial q_2}{\partial t_d} \cdot [1 - 2 \cdot \bar{J}] + \mu = 0 \quad (\text{A.17a})$$

$$\mu \cdot (t_d - \tau_2) = 0 \quad (\text{A.17b})$$

$$\mu \geq 0 \quad (\text{A.17c})$$

Since \bar{J} does not depend on t_d , the first term in eq.(A.17a) is zero. The first factor in the second term is negative, since q_2 is monotonically decreasing with respect to increasing t_d . Furthermore, \bar{J} is bounded above by 0.5. The latter derives from the interpretation of J as the detection error probability of the team when $q_2 = 0$. A value of $J \geq 0.5$ implies that the thresholds are being used to give observations an opposite interpretation, which results in worse than chance behavior. Assuming that the minimization in eq.(16) assures that at least chance performance will obtain, i.e. that $\bar{J} < \min(p_0, p_1) \leq 0.5$, then eq.(A.17) implies that $t_d = \tau_2$. In other words, always place the deadline at the maximum allowable. This result is valid independent of \bar{T}_{p_1} and \bar{P} values.

Using Unconstrained Optimal Thresholds

Continuing with examination of the inner minimization, consider the question of whether the unconstrained optimal thresholds t_{1j}^* can be a solution to Problem A2. Because of the reformulation in terms of \bar{P} and the stagewise minimization structure, this question must be answered in a more general way. Whereas the minimization in eq.(A.16) resulted in the construction of two functions $\bar{t}_{2j}(\bar{T}_{p_1}, \bar{P})$, minimization of J without the constraint in eq.(A.16) results in two different functions that represent the unconstrained optimal values of t_{1j} for a given \bar{P} value. Denote these functions by $t_{1j}^*(\bar{P})$. Written explicitly, they are

$$t_{20}^* = \frac{2(\sigma_2)^2 \log(p_{01}/p_{00}) + (m_{20})^2 - (m_{21})^2}{2(m_{20} - m_{21})} \quad (A.18)$$

$$t_{21}^* = \frac{2(\sigma_2)^2 \log(p_{11}/p_{10}) + (m_{20})^2 - (m_{21})^2}{2(m_{20} - m_{21})} \quad (A.19)$$

Note that eq.(A.18) and eq.(A.19) include the values of t_{2j} that are found in γ_2^* ; they are obtained by setting $\bar{P} = \bar{P}(t_2^*, 0)$.

To resolve the issue at hand, therefore, the investigation proceeds in terms of \bar{P} and considers whether $t_{2j}^*(\bar{P})$ represent a possible solution to the inner stage minimization. Denote by $T_{p2}^*(\bar{P})$ the processing time required by the second member when unconstrained optimal thresholds are used. Setting $t_d = \tau_2$ in Problem A2, the inner stage minimization becomes that of finding a value of \bar{T}_{p2} that solves

$$\frac{\partial \bar{J}}{\partial \bar{T}_{p2}} \cdot [1 - 2 \cdot q_2] + \frac{\partial q_2}{\partial \bar{T}_{p2}} \cdot [1 - 2 \cdot \bar{J}] = 0 \quad (A.20)$$

In particular, it is of interest whether $T_{p2}^*(\bar{P})$ satisfies eq.(A.20). Because $T_{p2}^*(\bar{P})$ represents a global minimum of \bar{J} , the first term in eq.(A.20) is zero. Now, if $T_{p2}^*(\bar{P}) \leq \tau_2$, the second term is also zero, since q_2 does not depend on \bar{T}_{p2} in this region. Thus unconstrained optimal thresholds are solutions when the processing time they require does not exceed the deadline. This is reasonable, since any adjustment of thresholds would have no effect on input/output errors; hence the thresholds can be left at their unconstrained optimal values.

However, for $T_{p2}^*(\bar{P}) > \tau_2$, a different result obtains. In this situation, q_2 is monotonically increasing with \bar{T}_{p2} . Furthermore, since $\bar{J} < 0.5$, as discussed earlier, it is true that the second term is non-zero. Hence $T_{p2}^*(\bar{P})$ does not satisfy eq.(A.20). This result means that if the processing time required by use of the unconstrained optimal threshold values is greater than that allowed, it is always desirable to adjust t_{20} ,

and t_{s1} to reduce T_{p2} and thereby reduce the input/output error q_2 .

Minimizing Second Member Input/Output Errors

The discussion above has concluded that, when it is an issue, it is more advantageous to reduce the second member's input/output errors than to retain the best thresholds. The question arises as to whether input/output errors should be minimized as much as possible, at the expense of the threshold settings. In terms of Problem A2, this issue is one of whether $\bar{T}_{p2} = \tau_2$ is a solution to the inner minimization, given that $T_{p2}^*(\bar{P}) > \tau_2$, or whether $\bar{T}_{p2} > \tau_2$ is a solution instead. Its resolution depends on how drastically the trade of speed for accuracy is made by the team member, which is modeled by the parameter f_s .

To properly investigate this issue, it is necessary to add another constraint to Problem A2 in the inner stage that restricts values of \bar{T}_{p2} to be larger than τ_2 , which is the region of interest. The result is the problem

$$\begin{aligned} \min_{\bar{T}_{p2}} \quad & \left\{ \bar{J}(\bar{P}, \bar{T}_{p2}) + [1 - 2 \cdot \bar{J}(\bar{P}, \bar{T}_{p2})] \cdot q_2(\bar{T}_{p2}, \tau_2) \right\} \\ \text{s.t.} \quad & \tau_2 \leq \bar{T}_{p2} \end{aligned} \quad (A.21)$$

where it is assumed that $T_{p2}^*(\bar{P}) > \tau_2$. The necessary conditions for a solution value of \bar{T}_{p2} are

$$\frac{\partial \bar{J}}{\partial \bar{T}_{p2}} \cdot [1 - 2 \cdot q_2] + \frac{\partial q_2}{\partial \bar{T}_{p2}} \cdot [1 - 2 \cdot \bar{J}] - \mu = 0 \quad (A.22a)$$

$$\mu \cdot (\tau_2 - \bar{T}_{p2}) = 0 \quad (A.22b)$$

$$\mu \geq 0 \quad (A.22c)$$

and the issue is whether $\bar{T}_{p2} = \tau_2$ is a solution to (A.21). If so, $\mu > 0$. In addition, it must be true that the first two terms in (A.21a) are positive in sum. It happens that the second of the two is always positive, as discussed previously. However, the first is always negative for $\tau_2 \leq \bar{T}_{p2} \leq T_{p2}^*(\bar{P})$. This is because $q_2 < 0.5$, which is again the assumption that the second member's processing behavior is better than

chance level. Furthermore, for $\bar{T}_{p2} \in [\tau_2, T_{p2}^*(\bar{P})]$, \bar{J} monotonically decreases with increasing \bar{T}_{p2} . That is, as \bar{T}_{p2} forces the thresholds t_{20} and t_{21} to move away from $t_{2j}^*(\bar{P})$, \bar{J} increases. Together, these two facts mean that the first term in (A.22a) is negative.

Thus it is unclear whether $\bar{T}_{p2} = \tau_2$ satisfies (A.22a). A more specific test to resolve the ambiguity can be derived as follows. At $\bar{T}_{p2} = \tau_2$, q_2 is at its minimum: $q_2 = (1 + \exp(f_m))^{-1} \triangleq q_{2m}$. Furthermore

$$\frac{\partial q_2(\tau_2, \tau_2)}{\partial \bar{T}_{p2}} = f_s \cdot e^{f_m \cdot (q_{2m})^{-2}} \quad (\text{A.23})$$

Substituting (A.23) into (A.22a) and rearranging gives

$$f_s > - (q_{2m})^2 \cdot (e^{-f_m}) \cdot \left[\frac{1 - q_{2m}}{1 - \bar{J}(\bar{P}, \tau_2)} \right] \cdot \frac{\partial \bar{J}(\bar{P}, \tau_2)}{\partial \bar{T}_{p2}} \triangleq F_s \quad (\text{A.24})$$

which must be satisfied if $\bar{T}_{p2} = \tau_2$ is a solution. F_s is a non-negative quantity that depends on \bar{P} . The parameter f_s models the rate at which input/output errors increase as the processing time required increases beyond the deadline. If $f_s > F_s$, then the marginal increase in q_2 is great enough so that it is optimal to minimize input/output errors and to adjust thresholds accordingly. If $f_s < F_s$, then there exists a compromise between the two extremes - minimum q_2 at $\bar{T}_{p2} = \tau_2$ or minimum \bar{J} at $\bar{T}_{p2} = T_{p2}^*$ - that gives better overall team performance.

Summary of Second Member Solution Characteristics

Three specific issues regarding the placement of t_{20} , t_{21} and t_d to solve Problem A1 have been considered in the foregoing paragraphs. Because of the stagewise minimization solution technique, the conclusions reached are in terms of \bar{P} . Figure A.5 illustrates the speed/accuracy loci for a given \bar{P} value and also summarizes graphically the conclusions regarding the inner stage minimization.

First, it has been shown that t_d should always be set at τ_1 so that

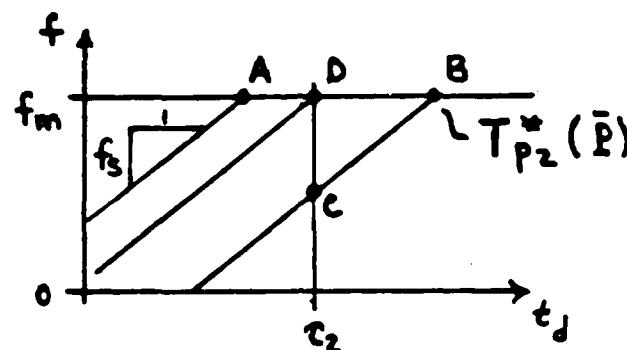


Figure A.5 Illustration of Inner Minimization Results

the member can use all the time available. In terms of Figure A.5, this means that possible solution points are limited to one of two regions. One is along the $f = f_m$ line from $t_d = 0$ up to $t_d = \tau_2$. This region corresponds to where $T_{p2}^*(\bar{P}) < \tau_2$, which might give a solution such as at point A. The other region is along the $t_d = \tau_2$ line. Solutions will be on this line when $T_{p2}^*(\bar{P}) \geq \tau_2$, which is the case shown in Figure A.5. Point B is where $T_{p2}^*(P) = t_d$ and represents the lowest value of t_d for which maximum accuracy can be achieved using the unconstrained optimal thresholds $t_{2j}^*(\bar{P})$.

Second, for the case where $T_{p2}^*(\bar{P}) < \tau_2$, i.e. for the situation represented in Figure A.5 by point B, it has also been shown that it is always optimal to adjust the thresholds away from $t_{2j}^*(\bar{P})$. In terms of Figure A.5, this means that point C is not a solution to Problem A2. Rather, the solution lies somewhere between points D and C, possibly exactly at point D. Point D represents the adjustment of thresholds t_{2j} so that accuracy is maximized. Whether or not this is desirable depends on the characteristics of \bar{J} at point D and also on the slope of the speed/accuracy loci. The tradeoff is as follows. Moving the operating point away from D toward C means that the thresholds are in some sense closer to $t_{2j}^*(P)$ and therefore of higher quality. It also means that input/output accuracy decreases. Thus if the performance gained because of threshold improvement exceeds that lost because of accuracy degra-

dation, a solution point between D and C will be selected. A test for whether this is the case has been derived, which compares the parameter f_s with characteristics of operating at point D.

A.3.3 First Member Solution Characteristics

Discussion thus far has considered solution characteristics in terms of \bar{P} , and the conclusions reached pertain to the second member. Turning now to the outer minimization in Problem A1, there are several questions that arise. One is whether the solution ever involves guessing by the first member. A related question is to what extent the guessing bias influences solution characteristics. To resolve these issues it is useful first develop a geometric representation of how feasible (t_1, q_1) values map to values of \bar{P} , and then to consider the solution of Problem A1 in terms of this framework.

Geometric Representation of P Values

For given a priori probabilities on H (i.e. p_0, p_1), all possible P values can be represented in the (p_{00}, p_{11}) plane, and in fact describe a region typically as shown in Figure A.6. The construction is as follows.

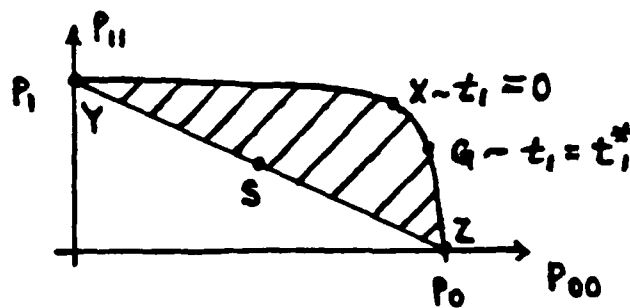


Figure A.6 Typical Region of P Values in (p_{00}, p_{11}) Plane

First, for $q_1 = 0$, a locus of points $(p_{00t}(t_1), p_{11t}(t_1))$ is determined in the (p_{00}, p_{11}) plane. In the figure, points Y and Z correspond to where $t_1 \rightarrow -\infty$ and $t_1 \rightarrow +\infty$, respectively. As t_1 moves from $-\infty$ to $+\infty$ the locus determined has many properties in common with the usual Receiver Operating

Characteristic [27] used in signal detection theory. In particular, it is convex. Furthermore, as the ability of the first member to discriminate between $H = H^0$ or $H = H^1$ improves, the locus moves closer to the $p_{11} = p_1$ horizontal and $p_{00} = p_0$ vertical lines, with perfect discrimination represented by the point $(p_{00}, p_{11}) = (p_0, p_1)$. As will be seen shortly, the locus $(p_{00t}(t_1), p_{11t}(t_1))$ is the upper boundary of the region of possible \bar{P} values in the (p_{00}, p_{11}) plane.

At the other extreme, if $q_1 = 1$, then a single point in the (p_{00}, p_{11}) plane is determined: $(g_1 p_0, (1-g_1) p_1)$. This point falls on the diagonal from point Y to point Z in Figure A.6, and its actual location depends on the values of the guessing bias g_1 . Point S corresponds to $g_1 = 0.5$, and points Y and Z correspond to $g_1 = 0$ and $g_1 = 1.0$, respectively. Now consider the points (p_{00}, p_{11}) that are generated when q_1 and t_1 range over their possible values. For simplicity, assume that $g_1 = 0.5$. Then for each value of t_1 , as q_1 moves from 0 to 1 a linear locus in the (p_{00}, p_{11}) plane is determined that extends from the $(p_{00t}(t_1), p_{11t}(t_1))$ locus to the point S. For given values of g_1 , the mapping from (t_1, q_1) to (p_{00}, p_{11}) is 1-1 and in fact determines a closed bounded region such as the one shown in Figure A.6. Note that all points off the upper boundary represent non-zero guessing, and that the unconstrained optimal operating point is itself somewhere in the upper boundary as illustrated by point G in the figure.

While Figure A.6 represents possible \bar{P} values, not all of them will be feasible due to the constraint on T_{p1} . Specifically, for given τ_1 , the constraint requires t_1 and q_1 to be such that

$$(t_1)^2 \leq \sqrt{\frac{a_1 - \tau_1}{b_1}} \quad (\text{A.25})$$

Figure A.7a shows typically how eq.(A.25) restricts \bar{P} values for $d_1 = 0$, i.e. when the first member has no switching overhead. A guessing bias of 0.5 has been assumed. The arc ACB represents the locus where $T_{p1} = \tau_1$, and the shaded area designates the region of feasible P values. A similar

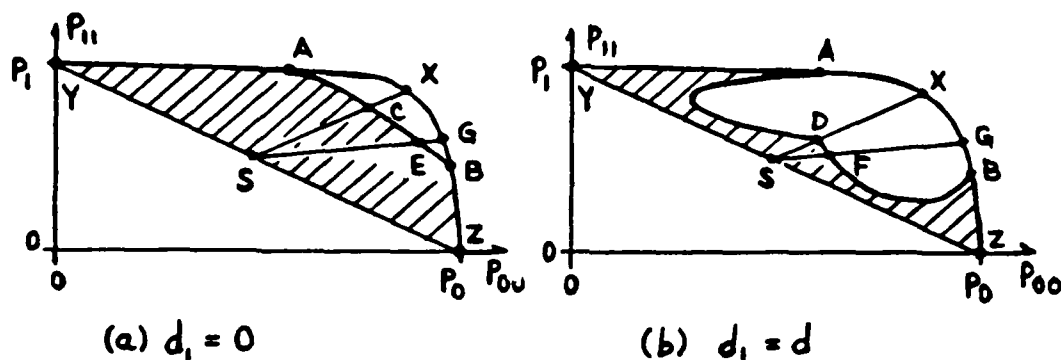


Figure A.7 Constraint on T_{p1} in (p_{00}, p_{11}) Plane; $g_1=0.5$

depiction is given in Figure A.7b for the case where d_1 has increased from zero to a relatively significant value. Again, the arc ADB represents the locus where $T_{p1} = \tau_1$. Note that the symmetry in eq.(A.25) about zero for t_1 values maps into the (p_{00}, p_{11}) plane as a symmetry of sorts about the XS locus. (Recall from Figure A.6 that by definition point X is where $t_1 = 0$ and $q_1 = 0$.)

Solution Characteristics

The solution to Problem A2 is found by searching over regions such as those in Figure A.7. It is not necessary to consider every feasible (p_{00}, p_{11}) point, however. Rather, it is known that the solution must lie on the upper boundary of the feasible region, as will now be shown.

Consider again the region in the (p_{00}, p_{11}) plane that represents possible \bar{P} values. Denote this region by R, and also define q_0 to be the quantity $p(u=0)$. In terms of P,

$$q_0 = p(u=0) = p_{00} + p_{01} = p_{00} + p_1 - p_{11} \quad (\text{A.26})$$

In the (p_{00}, p_{11}) plane, constant q_0 contours are lines with positive slope, as shown in Figure A.8. For each q_0 value there exists two (p_{00}, p_{11}) pairs on the boundary of R. Denote the pair on the lower diagonal boundary by $(p_{00g}(q_0), p_{11g}(q_0))$ and the pair on the upper right boundary by $(p_{00u}(q_0), p_{11u}(q_0))$. Then all possible (p_{00}, p_{11}) values in R can be determined from values of q_0 and δ using the expression

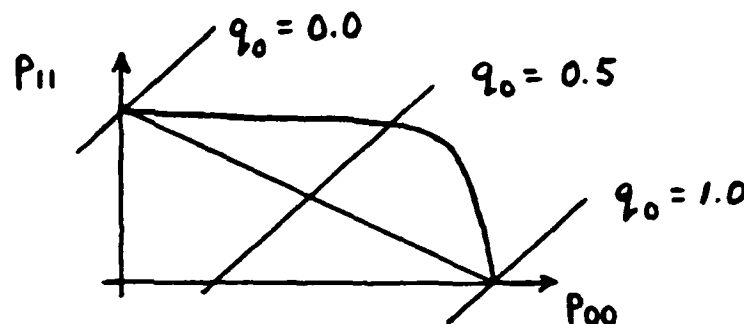


Figure A.8 Constant q_0 Contours in (p_{00}, p_{11}) Plane

$$\begin{bmatrix} p_{00} \\ p_{11} \end{bmatrix} = (1-\delta) \cdot \begin{bmatrix} p_{00g}(q_0) \\ p_{11g}(q_0) \end{bmatrix} + \delta \cdot \begin{bmatrix} p_{00u}(q_0) \\ p_{11u}(q_0) \end{bmatrix} ; \delta \in [0,1] \quad (\text{A.27})$$

Conversely, only values in R can be reached by eq.(A.27). In searching over feasible \bar{P} values to accomplish the outer minimization and thereby solve Problem A1, it is therefore possible to search over (q_0, δ) pairs, which adds considerable focus to the minimization process.

To set up the general solution in terms of using (q_0, δ) pairs, consider first a special case of Problem A1 where the constraint on the first member is not binding and all possible \bar{P} values are feasible. In terms of q_0 and δ , Problem A1 can be written as

Problem A3

$$\min_{q_0, \delta} \left\{ \min_{t_{10}, t_{11}} \left\{ q_2 + (1-2q_2) \cdot J \right\} \right\}$$

In Problem A3, the fact that $t_d = \tau_1$ has been used to eliminate the constraint on t_d . Furthermore, eq.(A.27) is to be used to map (q_0, δ) pairs into values of \bar{P} . An equivalent problem is obtained by rearranging the order of minimization:

$$\min_{q_0} \left\{ \min_{t_{20}, t_{21}} \left\{ \min_{\delta} \left\{ q_2 + (1-2q_2) \cdot J \right\} \right\} \right\}$$

The advantage of doing so is that for given t_{20} , t_{21} , and q_0 the value of q_2 is fixed. This means that minimization over δ affects only J . As a shorthand, define

$$\bar{q} \left(\frac{t_{2j} - m_{2k}}{\sigma_2} \right) \triangleq \bar{q}_{jk} \quad j, k \in \{0, 1\} \quad (\text{A.28})$$

Substituting eq.(A.28) into eq.(A.15) and rewriting in terms of (q_0, δ) , J can be expressed as

$$\begin{aligned} J(\bar{P}, t_{20}, t_{21}) = & \left[(1-\delta) \cdot p_{00u}(q_0) + \delta \cdot p_{00g}(q_0) \right] \cdot (\bar{q}_{10} - \bar{q}_{00}) + p_0 \cdot (1-q_0) \\ & + \left[(1-\delta) \cdot p_{11u}(q_0) + \delta \cdot p_{11g}(q_0) \right] \cdot (\bar{q}_{11} - \bar{q}_{01}) + p_1 \cdot q_0 \end{aligned} \quad (\text{A.29})$$

For given values of t_{20} , t_{21} , and q_0 consider the minimization over δ in eq.(A.29). Differentiate with respect to δ . The result yields

$$\begin{aligned} \frac{\partial J}{\partial \delta} = & \left[p_{00g}(q_0) - p_{00u}(q_0) \right] \cdot (\bar{q}_{10} - \bar{q}_{00}) \\ & + \left[p_{11g}(q_0) - p_{11u}(q_0) \right] \cdot (\bar{q}_{11} - \bar{q}_{01}) \end{aligned} \quad (\text{A.30})$$

Because of the parameterization in terms of q_0 and the properties of R , it is true that

$$p_{00g}(q_0) \leq p_{00u}(q_0) \quad (\text{A.31})$$

$$p_{11g}(q_0) \leq p_{11u}(q_0) \quad (\text{A.32})$$

Equality in eq.(A.31) and eq.(A.32) only occurs at the extremes where $q_0 = 0$ or 1 . Since these two situations are not of particular interest with respect to subsequent conclusions, a strict inequality can be assumed. Now, if $t_{21} < t_{20}$, then strict inequalities exist between \bar{q}_{1k} and \bar{q}_{0k} :

$$\bar{q}_{10} < \bar{q}_{00} \quad (A.33)$$

$$\bar{q}_{11} < \bar{q}_{01} \quad (A.34)$$

In this situation, the right hand side of eq.(A.30) is strictly positive, which means that J increases with increasing δ . Thus the minimizing δ is 0, which means that the solution is on the upper boundary of R . A complementary situation obtains for $t_{10} < t_{11}$: $\delta = 1$ and the solution is on the lower boundary. For the case where $t_{10} = t_{11}$, any value of δ is a solution; $\delta = 0$ is arbitrarily specified.

Since the observations made with respect to eq.(A.30) are valid for any q_0 , the general conclusion is that solutions to Problem A1 are such that they fall on the boundary of R . Furthermore, it can be argued on intuitive grounds that the solution must be on the upper boundary. This is reasoned as follows. For given q_0 , knowing that $\delta = 0$ or 1 in effect reduces Problem A3 to two minimizations over t_{10} , t_{11} :

$$\min_{t_{10}, t_{11}} \left\{ q_1 + (1-2q_2) \cdot J_u(q_0) \right\} \quad (A.35)$$

$$\min_{t_{10}, t_{11}} \left\{ q_1 + (1-2q_2) \cdot J_g(q_0) \right\} \quad (A.36)$$

where J_u and J_g represent the values of J on the upper and lower boundaries of R , respectively. By analogy with the Receiver Operating Characteristic, however, the lower boundary represents purely random responses by the first member. In addition, since q_0 is specified the effect on q_1 by the first member is the same in eq.(A.35) and eq.(A.36). Finally, there are no restrictions on t_{1j} in either case. The issue is whether the solution in (A.35) yields a smaller J_0 than in (A.36). Since (A.35) represents operation at a point where the first member is providing some useful indication to the second member, it can be concluded that the team can do no worse in (A.35) than in (A.36), because in the latter case no useful information is provided by the first member.

The foregoing discussion has been made for the special case where the entire region of realizable (p_{00}, p_{11}) pairs was also feasible. If the

processing time constraint on the first member is binding, then not all of R is feasible as illustrated in Figure A.7. The parameterization of (p_{00}, p_{11}) pairs in terms of q_0 and δ must be adjusted in this case so that only feasible (p_{00}, p_{11}) pairs are obtained. This can be done simply by restricting δ . That is, for each q_0 value there will be a set of δ values that correspond to feasible (p_{00}, p_{11}) pairs. Denote this set by $\Delta(q_0)$. Thus Problem A3 is modified to be that of

Problem A3 (Modified)

$$\begin{aligned} \min_{q_0, \delta} \quad & \left\{ \min_{t_{10}, t_{11}} \left\{ q_2 + (1-2q_2) \cdot J \right\} \right\} \\ \text{s.t. } & \delta \in \Delta(q_0) \end{aligned}$$

The arguments made earlier with respect to

$$\frac{\partial J}{\partial \delta}$$

are unchanged, however. It is still desirable to place δ at either its maximum or minimum value. This means that solutions to Problem A3 will either be on the lower diagonal or on the upper boundary of the region representing feasible (p_{00}, p_{11}) values. Furthermore, the same line of reasoning can be used to argue that the upper boundary represents a uniformly better solution point for a given q_0 . Taking this to be the case, the general conclusion is that solution to Problem A1 is such that either

$$q_1 = 0 \text{ or } T_{p1} = \tau_1 \tag{A.37}$$

In terms of Figure A.7, (A.37) means that the solution must be on the arcs YACBZ or YADBZ, respectively. In particular, it is possible that solutions will be obtained on the arcs ACB or ADB; in other words it may be optimal to guess. This can be explained qualitatively as follows. All other things being equal (i.e. neglecting the second member), it is desired to operate in the (p_{00}, p_{11}) plane as close as possible to the point where $q_1 = 0$ and $t_1 = t_1^*$. In Figure A.7, neither region admits the

unconstrained optimal solution as feasible. In Figure 7a, however, point E is closer than point B, where the former is such that $q_1 \neq 0$ and the latter is the nearest feasible point where $q_1 = 0$. In Figure 7b, point B is closer to the unconstrained optimal point. Thus the situation in (a) is likely to have a solution where $q_1 \neq 0$, while in (b) the solution will likely be at point B.

Effect of Guessing Bias

Given the framework and analysis presented, it is straightforward to consider the effect that guessing bias has on the problem solution. Figures A.6 and A.7 were constructed assuming a 50/50 guessing bias, i.e. $g_1 = 0.5$. As mentioned earlier, exclusive guessing ($q_1 = 1$) determines a single operating point in the (p_{00}, p_{11}) plane along the diagonal from $(0, p_1)$ to $(p_0, 0)$. Since the upper boundary of R is unchanged by changes in g_1 , the region of possible (p_{00}, p_{11}) pairs is always the same irrespective of where point S lies on the diagonal. However, because the constraint on processing time is in some sense symmetric about the XS segment due to the form of eq. (A.25), the region of feasible (p_{00}, p_{11}) pairs is altered when g_1 changes. Figure A.9 shows the same constraints

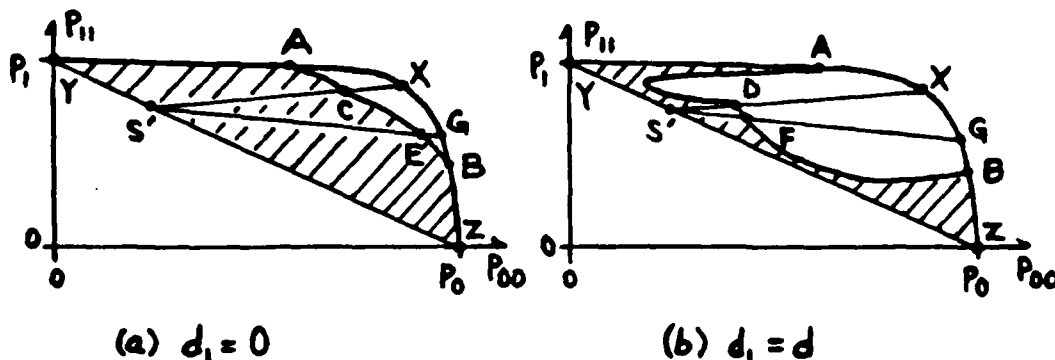


Figure A.9 Constraint on T_{p1} in (p_{00}, p_{11}) Plane: $g_1 = 0.75$

as Figure A.7, except that g_1 is set to be 0.75. For this case, the pure guessing point is at S', which is at 25% of the YZ distance from Y.

Though the actual region of feasible (p_{00}, p_{11}) values changes with g_1 , the qualitative characteristics of the problem solution do not. Thus

the solution is to be found on the region's boundary, in particular along the upper boundary of the feasible region. Furthermore, solutions with $q_1 \neq 0$ and with $t_1 \neq t_1^*$ are also possible and even likely, depending on how the constraint restricts (p_{00}, p_{11}) values.

Reversing Signals - An Alternate Solution

A significant aspect of the solution for the first member's operating point is evident by examining the problem in terms of the (p_{00}, p_{11}) plane. Whereas the "performance" that is possible for the member (as determined by the ability to discriminate between H values) has the usual convex ROC-like shape, the addition of a workload constraint changes the region of feasible operating points so that can be decidedly non-convex. This highlights the fact that workload and performance, while they may depend on the same underlying parameters, are two different measures. Thus when both are represented in the same coordinate framework there is no guarantee that both will exhibit the same properties in that frame.

As a further example that workload and performance are distinct but related, the following discussion outlines how better overall team performance can be realized, because of workload constraints, if individual members reverse the interpretation of the signal that is sent between them. That is, if the first member declares $u = 0$ when $y_1 > t_1$ and the second member is assigned thresholds t_{2j} such that he is biased to say $v = 0$ when $u = 1$, a consistent end-to-end association of H values with v values will have been made, since the reversals within the team cancel each other. The potential advantage of doing so, however, is that the workload of the second member can be significantly altered, and thereby lead to improved overall team performance.

To show how reversing signals can be of advantage, an example will be constructed. First, consider the implication of reversing the assignment of u values with respect to y_1 . In terms of the (p_{00}, p_{11}) plane, the result is that a new region of (p_{00}, p_{11}) pairs are now possible, as shown in Figure A.10. Points above the diagonal are realized by associating

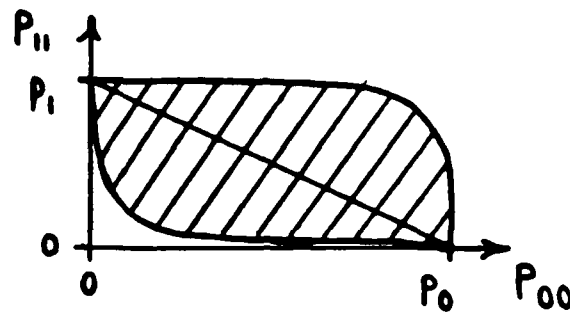


Figure A.10 Augmented Region of Possible (p_{00}, p_{11}) Pairs

$u = 1$ if $y_1 > t_1$; points below the diagonal are realized when $u = 0$ is declared for $y_1 > t_1$. The points below the diagonal are obtained from those above by reflecting through the point $(.5p_0, .5p_1)$.

The outer minimization in Problem A1 is thus conducted over a larger region of (p_{00}, p_{11}) pairs. However, the analysis completed earlier by parameterizing R in terms of q_0 and δ is still valid. In particular, the solution point will still be on the boundary of R , even though the characteristics of R have changed somewhat. Recall that it will be on the upper boundary if $t_{10} > t_{11}$; it will be on the lower boundary if $t_{10} < t_{11}$. In this case, however, both the upper and lower boundaries represent useful information to be forwarded to the second member. Furthermore, the solution will be such that the information is used consistently with respect to overall detection performance. That is, on the upper boundary $u = 1$ will bias the second member in favor of $H = H^1$ since $t_{11} < t_{10}$; on the lower boundary $u = 1$ will bias the second member in favor of $H = H^0$ since $t_{11} > t_{10}$.

In obtaining the original unconstrained detection decision rules, there were two equivalent solution possibilities. One corresponded to operation on the lower boundary of R and the other on the upper. The addition of processing limitations on the second member, however, can make one of these solutions more desirable than the other as will now be illustrated. Suppose that the unconstrained optimal solution is such that $q_0^* = 0.5$, i.e. each threshold t_{ij}^* is used an equal percentage of the time.

Select the solution that puts $t_{11}^* < t_{10}^*$ and which assumes $u = 1$ when $y_1 > t_{11}^*$. Now consider what happens when the speed/accuracy tradeoff model of the second member's processing behavior is added. In particular, assume that $b_{10} > b_{11}$, which means that threshold t_{11} requires less workload than t_{10} .

The situation described above is illustrated in terms of the (t_{10}, t_{11}) plane in Figure A.11. Point A is the unconstrained optimal

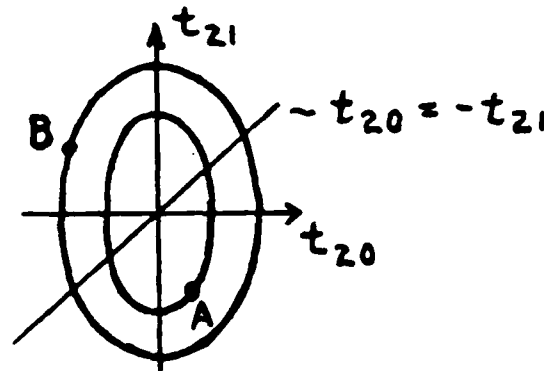


Figure A.11 Illustration of Second Member Operation in (t_{10}, t_{11}) Plane operating point chosen. Point B is the equivalent performance point obtained by interchanging values of t_{10} and t_{11} and reversing the assignment of u . The two ellipses in the figure are constant T_{p2} contours. Given that $q_0^* = 0.5$, the relationship between b_{10} and b_{11} determines their eccentricity. The outer ellipse corresponds to a lower value of T_{p2} (see eq.(A.8)); in particular, it is true that

$$T_{p2}^A > T_{p2}^B \quad (A.39)$$

Given the model of the second member's behavior, so long as $\tau_2 \geq T_{p2}^A$, the solution to Problem A2 will leave the operation at $t_{2j} = t_{2j}^*$, which is in fact the best that the team can do given the upper limit on the second member's input/output accuracy. (For purposes of exposition, it is assumed that the first member's constraint is not a factor.) When $\tau_2 < T_{p2}^A$, then leaving t_{2j} at point A means that input/output accuracy will decrease. However, because point B represents a smaller T_{p2} value, it is

possible to retain the better performance level by reversing the assignment of u and interchanging thresholds t_{2j} .

Though q_0^* has been assumed to be 0.5 in this example, the result demonstrated does not require this to be the case. Basically, because there are inequalities in processing time for using each threshold t_{2j} , there exists the possibility that this can be exploited. If by reversing u assignment a seldom-used but low-workload threshold type can be made into an often-used threshold that in turn lowers overall processing load, then this can be of advantage with respect to overall team performance.

Summary of First Member Characteristics

Using geometrical arguments, the solution characteristics for the outer minimization in Problem A1 have been examined. It was shown that guessing can be desirable in some situations and that the guessing bias can have an effect on the relative attractiveness of guessing as part of the solution. A general result was that solutions must exist either where $q_1 = 0$, $q_1 = 1$, or $T_{p1} = \tau_1$. In the (p_{00}, p_{11}) plane this places the solution on the boundary of feasible (p_{00}, p_{11}) pairs. It was further argued that $q_1 = 1$ is not a solution characteristic, since for every possible $q_1 = 1$ solution, there exists a better one either where $q_1 = 0$ or where $T_{p1} = \tau_1$.

Finally, the possibility of reversing the assignment of u was considered, and it was demonstrated by example that this can result in better team performance. The underlying principle that leads to this conclusion is of general importance. It is that processing load and performance, though dependent on the same fundamental quantities, are distinct, and two operating points that are indistinguishable from the point of view of performance may be significantly different when processing load requirements are taken into account.

A.4 Special Case

To further highlight particular mechanisms of how one member can affect the other and also team performance, consider the following special case. Suppose that the second member's processing time is independent of the threshold positions, but that it takes longer to use threshold t_{20} than t_{21} . Also, assume that the switching overhead for the second member is significant and that the deadline τ_2 affects the use of t_{20} but not that of t_{21} . That is, mathematically assume that

$$b_{2j} = 0; \quad a_{20} > \tau_2 > a_{21} \quad (\text{A.40})$$

Finally, assume that the first member's constraint is not active. For this special case, Problem A1 can be summarized in terms of Figure A.12.

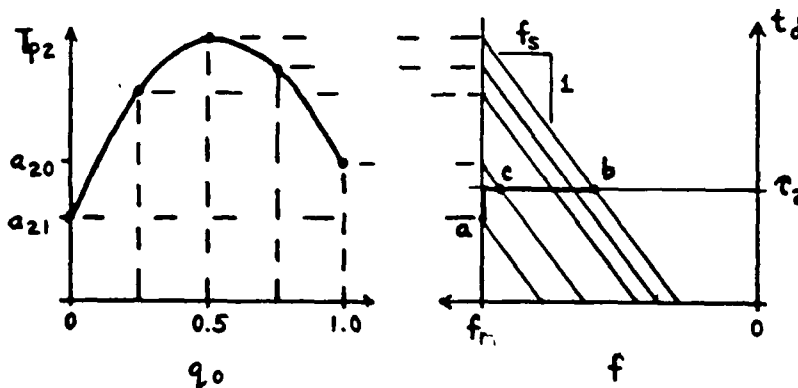


Figure A.12 Illustration of Special Case Solution

Since T_{p2} is independent of t_{2j} , its variation is due entirely to variation in q_0 , which is determined by the first team member through placement of t_1 . The dependence of T_{p2} on q_0 is shown in the left part of Figure A.12. The relationship between T_{p2} and input/output accuracy is shown in the right part of the figure. Recall from eq.(A.11) that a given value of T_{p2} determines a locus of f values as a function of t_d . With $t_d = \tau_2$, a specific operating point on this locus is selected. As q_0 moves from 0 to 1, the resulting T_{p2} values trace out feasible operating points in the right part of the figure, moving from a to b and back to c. Each point on this locus has a minimum detection error probability, which is

An interesting feature of the minimization in this special case is that the tradeoff between speed and accuracy required for the second member is governed entirely by the first member. Furthermore, a reduction in T_{p_2} depends mostly on reducing the switching frequency. If t_1^* is somewhere near 0, then $q_0 \approx 0.5$ and the optimization problem is essentially one that must weigh two alternatives: either (a) degrade the first member's quality of processing by adjusting t_1 in order to reduce the second member's switching load and thereby improve f ; or (b) accept a lower input/output accuracy of the second member in favor of retaining a higher quality of processing by the first.

corresponds to increasing q_1 for two biases in guessing. Point H corresponds to the Problem A1 solution operating point (with $t_1 = t_1^C$). Points S and Y correspond to completely random operation with guessing biases of 0.5 and 0.0, respectively. The locus of where $q_0 = 0.5$ has also been shown.

As q_1 increases, the operating point moves away from H to either S or Y. Because the movement is toward the diagonal "guessing" line, team performance will generally be worse. A significant qualitative difference is apparent, however. Along the trajectory HS, T_{p2} is increasing and in fact comes to rest where switching frequency is at its maximum. Performance thus not only degrades because of changes in J but also because of an increase in q_1 . Along the trajectory HY, however, T_{p2} first rises due to the increase in switching, but decreases as switching overhead goes to zero. In this case, the contribution to performance degradation due to input/output errors is less. These two cases illustrate instances where rising processing load leads to worse performance, as well the situation where decreasing processing load also leads to worse performance. Furthermore, two operating points (S and Y) have been identified where the first member passes no information to the second, yet which have significantly different affects on the second member's processing load. Thus, even in this simple example, a variety of workload/performance relationships are possible, which underscores the importance of identifying and understanding how workload affects performance in more complex team problems.

A.5 Appendix Summary

This appendix has demonstrated that the addition of processing time constraints to a team theoretic problem modifies team operation. In particular, partially random behavior by team members can be optimal, either by a member's choice, through the selection of an option to guess; or by design, through selection of thresholds such that processing time exceeds a deadline, which in turn makes processing errors more likely.

A variety of relationships between individual processing load and team performance has also been shown to be possible or even desirable, including one in which each member in effect reverses his interpretation of the signal that is passed from one to the other. Though the net result

for the team is unchanged, the desirability of doing so stems from individual processing load considerations. The effect of switching overhead was seen in a special case to have a potentially significant impact on team behavior as well.

APPENDIX B

Support of Existence Proof

This appendix contains the details of the organization design carried out in Chapter 5. The appendix is organized according to the phases of the design process. The first section documents the analytic organization structure for the design (Phase I). The second section describes the details of decision rule implementations (Phase II). Finally, a third section integrates design elements (Phase III) and includes the results of various tests conducted on the organization design.

B.1 Analytic Organization Structure

The organization structure used for the detection task is that of a two-member, tandem distributed detection network, as shown below in Figure B.1 (also Figure 5.2). The specific values of parameters used in the

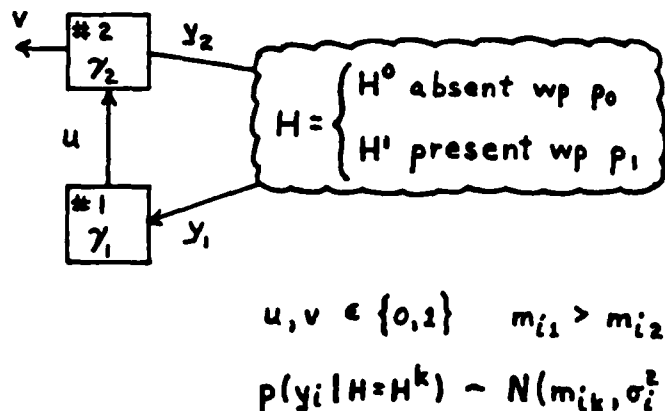


Figure B.1 Organization Structure

example design are given Table B.1. The decision rules that minimize organization detection error probability are known to be threshold tests whose form is given in eq.(5.5). Using the specific values given in Table

Table B.1 Organization Parameter Values

$m_{11} = -m_{10} = 0.8$	$\sigma_1 = 0.8$
$m_{21} = -m_{20} = 2.0$	$\sigma_2 = 1.5$
$p_0 = 0.4$	$p_1 = 0.6$

B.1, the decision rule thresholds for each member are

$$t_1^* = -0.05 \quad (B.1)$$

for the first member and

$$t_{20}^* = 0.75 \quad (B.2)$$

$$t_{21}^* = -1.12 \quad (B.3)$$

for the second member. Recall that decision rules represent ideal behavior of organization members. If this behavior were to be realized in the present case, organization detection error would be 0.06. That is, the analytic organization structure for the design yields

$$J_0(\gamma^*, \omega^N) = 0.06 \quad (B.4)$$

B.2 Decision Rule Implementations

B.2.1 First Organization Member

Task Situation

The first organization member's decision rule is implemented as illustrated in Figure B.2 (also Figure 5.3). The member is positioned before a CRT that always displays the square border and the circular dial. The threshold t_1 is also continuously displayed as a vertical line whose horizontal coordinate is the selected value of t_1 . An observation is

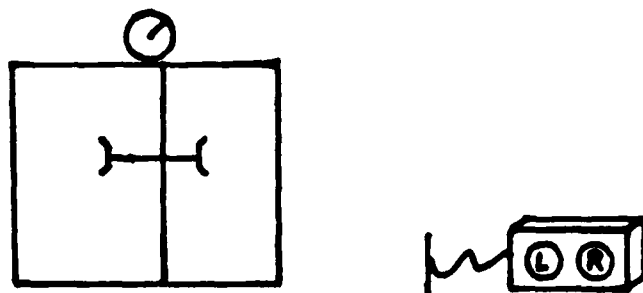


Figure B.2 First Member Task Situation

displayed as the pattern shown in the figure; horizontal pattern position is such that its midpoint corresponds to the value of y_1 . The display border is dimensioned to be 10 units (about 6 inches) on a side, with its upper right and lower left corners corresponding to the (5,5) and (-5,-5) coordinates, respectively.

The dial at the top of the task display is used to indicate the number of observations waiting to be processed. According to the design, the member must maintain an established rate of processing. The dial position advances clockwise as the number of observations waiting to be processed grows. The two mechanical buttons that serve as a response mechanism are mounted horizontally in a hand-held panel.

Information Processing Model

It is desired to develop a description of human behavior in accomplishing the task shown in Figure B.2. The description is to include a characterization of the realized input/output behavior, as well as the processing time required to perform the task. The member has been given two options for processing patterns. The first is to view the pattern carefully and to respond according to its position with respect to the threshold. A second option is to essentially ignore the pattern and to respond arbitrarily. These options have been labelled as Stimulus

Controlled Responses (SCR) and Fast Guesses (FG), respectively, and the information processing model must take both of them into account.

Consider first the description of human behavior when exercising only the SCR option. An information processing model was developed for this option as follows. In preliminary sessions, subjects were given ample experience with the task situation and with processing patterns at a variety of threshold settings. Once familiarity had been established, the responses and response times were recorded for a sequence of experimental conditions. Conditions differed only in their threshold setting. For each condition, two experimental runs were conducted; the first consisted of 50 trials and the second had 150 trials.

On each trial, an observation value y_1 was generated randomly according to its underlying distribution. A second random number, x_1 , was also drawn from a $N(0,1)$ distribution. To begin the trial, the pattern was displayed horizontally displaced by y_1 units and vertically displaced by x_1 units. The subject then viewed the pattern and judged it left or right with respect to the threshold, registering the judgement by depressing the appropriate mechanical button. The pattern then disappeared and an interval of time in which the display was blank intervened before the next trial. Blanking time was of random duration, as determined by a number drawn from a distribution that was uniform on the interval $[700,900]$ ms.

Subjects were instructed to respond as quickly as possible without sacrificing accuracy. No rate constraint was imposed (i.e. the dial did not move). Observations that fell within Δy units of the threshold setting were adjusted to be exactly Δy units from t_1 before they were displayed. This was done to prevent the situation where it was impossible to judge a pattern's position with respect to t_1 . In practice, about 5% of the patterns required adjustment, depending on the particular value of t_1 in use at the time.

Data was obtained from two subjects using the above procedure. Five

threshold values were selected from the interval

$$t_1 \in [m_{10} - \sigma_1, m_{11} + \sigma_1] \quad (\text{B.5})$$

For the underlying distribution on y_1 , the likelihood that y_1 will be within (B.5) is about 0.85 out of 1.00. Table B.2 lists the results

Table B.2 Observed SCR Results

Threshold t_1	Subject MP			Subject PO		
	\bar{t}_{SCR}	σ_{SCR}	P_{SCR}	\bar{t}_{SCR}	σ_{SCR}	P_{SCR}
-1.6	260	104	0.013	252	80	0.007
-0.8	300	85	0.040	279	77	0.000
0.0	329	99	0.027	290	59	0.007
0.4	331	102	0.027	328	94	0.013
0.8	314	83	0.027	281	76	0.027
1.6	274	112	0.020	262	100	0.027

observed for the second run of 150 trials. Included in the table are the average response time in milliseconds \bar{t}_{SCR} , the standard deviation of response times σ_{SCR} , and the fraction of errors P_{SCR} . Figure B.3 shows a

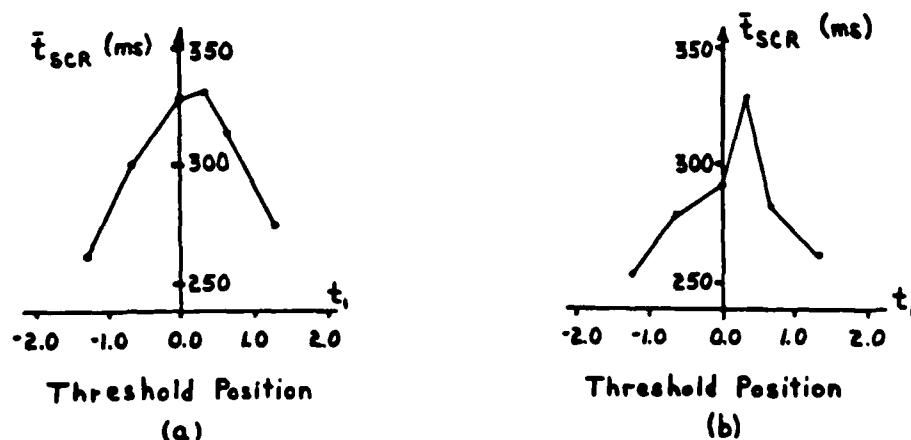


Figure B.3 Average SCR Time vs. t_1 (a) Subject MP (b) Subject PO

plot of \bar{t}_{SCR} versus threshold position t_1 . From the results shown, it is evident that SCR time decreases as the uncertainty decreases in the

response required. Furthermore, there is a significant variation in \bar{t}_{SCR} as t_1 ranges over the interval given in (B.5). Finally, the error rate in judging patterns is consistently small across the test conditions.

Given the results observed, the following description will be established for the SCR option:

$$\bar{t}_{SCR} = \bar{t}_{SCR} \text{ as given in Figure B.3} \quad (B.6)$$

$$\bar{k}_{SCR} : \begin{cases} \text{if } y_1 \geq t_1 & u = 1 \text{ wp } 1 \\ \text{else} & u = 0 \text{ wp } 1 \end{cases} \quad (B.7)$$

Eq.(B.6) assumes that values of \bar{t}_{SCR} for intermediate choices of t_1 can be obtained by interpolation. Eq.(B.7) effectively assumes that human input/output behavior is error-free. This, of course, is not evident in the data, but error rates are considered sufficiently low to justify this idealization within the model.

The second option provided to the member was that of fast guessing. Operationally, this corresponds to ignoring the pattern's actual position, and only responding to its appearance on the CRT. To determine a processing time characterization, subjects were required to fast guess on all trials of an experimental run, that is, they were instructed to respond as quickly as possible to the pattern's appearance. It is here that the random blanking interval between trials becomes significant, since it forces the subject to wait for the pattern to appear.

In order to distinguish deliberate fast guesses from quickly-made stimulus-controlled responses, subjects were instructed to fast guess by depressing both response buttons. While this experimentally dictated requirement means that fast guess responses are not really arbitrary, it is of little consequence from the first members' perspective. When the member chooses to fast guess, execution of this option is to respond "somehow" as quickly as possible. Whether this is by single or double button push is not important to him. Since double button pushes

unambiguously register fast guesses, the experimenter is effectively able to control the fast guessing bias by assigning $u = 0$ or 1 to these double button pushes at his discretion. The ability to do this will be used later when the organization is operated.

Average response time for fast guessing \bar{t}_{FG} was observed to be within an interval as shown in Table B.3. For purposes of later calculation

Table B.3 Observed Fast Guessing Results

Subject	Interval \bar{t}_{FG}	Selected Value
MP	[175,195]	180
PO	[165,185]	170

using the information processing models, a specific value of \bar{t}_{FG} has been selected for each subject. Since \bar{t}_{FG} is much lower than \bar{t}_{SCR} , it is evident that considerable leverage is possible with respect to reducing overall processing time when fast guessing. The following model for the fast guessing option will be adopted:

$$\bar{t}_{FG} = \bar{t}_{FG} \text{ from Table B.3} \quad (\text{B.8})$$

$$\bar{k}_{FG} : \begin{cases} u = 1 & \text{wp } 1-g_1 \\ u = 0 & \text{wp } g_1 \end{cases} \quad (\text{B.9})$$

In eq.(B.9), the parameter g_1 models the first member's bias toward choosing $u = 0$ when fast guessing, and is selected by the experimenter.

The complete information processing model for the first member is obtained by combining the two processing options according to their relative frequency of use. If the fraction of fast guessing is denoted by q_1 , then overall average processing time and input/output behavior are expressed as

$$T_{p1} = (1-q_1) \cdot \bar{t}_{SCR}(t_1) + q_1 \cdot \bar{t}_{FG} \quad (B.10)$$

$$\bar{k}_1 = (1-q_1) \cdot \bar{k}_{SCR}(t_1) + q_1 \cdot \bar{k}_{FG} \quad (B.11)$$

Using T_{p1} together with the processing rate requirement τ_1 , the workload measure and workload limit for the first member are given as

$$w_1 = (t_1)^{-1} \cdot T_{p1} \leq 1 = \bar{w}_1 \quad (B.12)$$

The validity of eqs.(B.11) and (B.12) as an information processing model has not been established at this point, and will be tested when the organization is operated. A key factor in the outcome will be whether the member can maintain the integrity of his options under stress. This is partially a matter of training and therefore an explicit part of the design. Earlier investigations of the Fast Guess model [28] offer evidence in support of human capability to accomplish a task of the present type by exercising two distinct processing options.

B.2.2 Second Organization Member

Task Situation

For the second organization member, a task situation that implements a two-threshold decision rule is required. The implementation to be used is shown in Figure B.4 (also Figure 5.5). The organization member is placed before a CRT that continuously displays a square border. Each side of the square measures 20 units (physically about 6 inches) and the upper right and lower left corners are at coordinates (10,10) and (-10,-10), respectively.

Depending on the value of u received, one of two display types is used to present an observation y_1 . If $u = 0$, the threshold t_{10} is displayed as a horizontal line whose vertical coordinate is the value of t_{10} . The observation y_1 is then displayed as a dot (actually a 0.2 unit

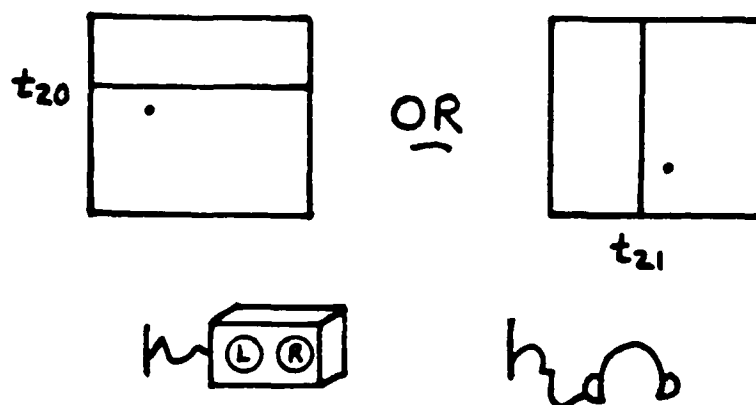


Figure B.4 Second Member Task Situation

circle), where its value is used as the vertical display coordinate. A complementary display type is used if $n = 1$: the threshold t_{21} is a horizontally displaced vertical line and the observed value of y_2 is also displayed as a horizontal coordinate. The organization member indicates his response to each observation by depressing one of two mechanical, horizontally-arranged buttons. If the dot is left (t_{21}) or below (t_{20}), a left button response is considered correct ($y_2 < t_{2j}$); if the dot is right (t_{21}) or above (t_{20}), a right button response is desired ($y_2 \geq t_{2j}$).

Because of the time allocation in the design, the second member is viewed as operating under the pressure of a deadline. As part of the task situation, the organization member hears a short tone burst when the deadline is reached. Thus the member must adjust his processing method so that he responds either before the tone burst or just as the tone is sounded.

Information Processing Model

As discussed in Chapter 5, the second member is to be operated deliberately in an overload region. Operationally, this means that processing time allowed will be insufficient compared with the time required to complete the task with negligible errors. Figure B.5 exhibits

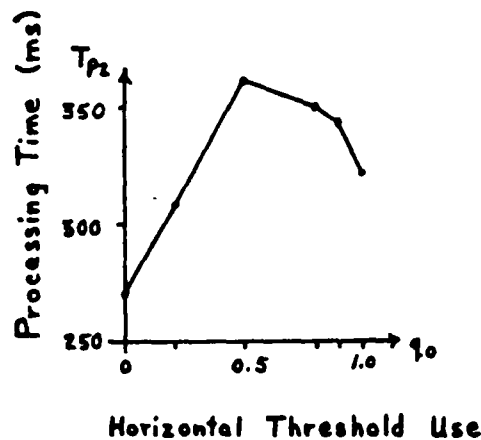


Figure B.5 Average Processing Time vs. Threshold Switching

results that are typical of the processing time requirements of the task. The data shown were obtained using the following procedure. With $t_{1,0} = t_{1,1} = 0$, several experimental runs of 200 trials were conducted. Experimental runs were distinguished by the amount of threshold switching required. This was determined by the value of q_0 , which is the fraction of threshold $t_{1,0}$'s use. On each trial a value of y_2 was generated randomly from an $N(0,2)$ distribution. A second random number was also drawn from an $N(0,2)$ distribution. These two numbers were used as dot position coordinates. The threshold selected for a given trial was determined by the outcome of an independent, binary (0,1) random variable with probabilities q_0 and $1-q_0$, respectively. Threshold and dot were then displayed simultaneously, and the response and response time were recorded for each trial. An 800 ms blanking time intervened between trials.

The results in Figure B.5 are from a subject who has been instructed to respond as quickly as possible, but correctly. The value of q_0 was not disclosed except to indicate whether it was 0, 1, or something in between, i.e. all horizontals, all verticals, or a mixture. Error rates of about 1-2% were observed for each experimental run. General characteristics evident in Figure B.5 include a significant amount of additional processing time for switching, and also a difference in processing time for horizontal and vertical threshold displays. These characteristics will be evident in the information processing model that is developed.

When the organization member does not have enough time to complete the task, he is forced to trade accuracy for speed. In the present context, if the deadline is selected so that it is less than T_{p2} , the member will exhibit a decrease in input/output accuracy as a consequence of shortening his response time to meet the deadline. Furthermore, as the degree of overload increases, accuracy will continue to decrease. This is a well-known effect from cognitive psychology [31], and the information processing model of the second member will be based on a particular representation of it.

The specific experimental procedure used to derive the second member's information processing model is as follows. Over several sessions, data were collected for six values of q_0 :

$$q_0 \in \{0.0, 0.2, 0.5, 0.8, 0.9, 1.0\} \quad (B.13)$$

In a given session, experimental runs of 200 trials were conducted at each condition, and the responses and response times were recorded. The generation, selection, and presentation of observation values and thresholds was done as described earlier. In addition, the deadline constraint was active and subjects were instructed to respond fast enough so that few beeps were heard. This process was repeated in separate sessions. The order in which conditions were presented changed in each session, and various deadline values were used, depending on the proficiency of the subject. All deadlines were selected so that the member would be overloaded, and several deadlines were used at each q_0 condition for each subject tested. Over several sessions (typically three), hundreds of responses were collected per subject per q_0 condition.

To construct a speed/accuracy representation using the data collected, a technique based on that of Lappin and Disch [32] has been used. First, all responses were rank-ordered by response time. Then these ordered responses were partitioned into groups containing several hundred trials each. An average response time was calculated for each

group, and the number of erroneous responses within each group was also determined. Finally, the so-called odds ratio, denoted OR, was computed for the group as the measure of accuracy, where

$$OR \triangleq \left(\frac{\# \text{ right}}{\# \text{ wrong}} \right) \quad (B.14)$$

Pew [29] has suggested that, for the type of task under consideration, there is a log-linear relationship between OR and processing time. Using this approach, the ordered and partitioned data for each q_0 condition have been plotted on semi-log coordinates for the subjects tested. These plots are given in Figures B.6-B.9.

The size of the partitions used (PS) has been recorded in each figure, as well as the total number of responses (SS). Note that the partition corresponding to the group of highest-valued response times has not been plotted for all subjects. In these cases the response time distribution has a long tail, and the computed average response time and odds ratio are not good approximations for a specific speed/accuracy point. Partition size selection is not critical to the representation of the data. A number of different sizes have been tried, with minimal impact on the information processing model that was eventually determined. The partitions finally used were selected to give a reasonable and representative depiction of the data for the region of t_d values of interest.

Subject KB is the author. Thus the eventual model form and the expected variation with respect to q_0 were known a priori to this subject. Even so, because of the technique used to develop the model, it is difficult to manufacture data for this task. Thus the data obtained from subject KB are believed to not be uncharacteristic of the task, although they do represent results from someone who has had considerable practice at the task.

From the figures, it is evident that the log-linear model is a reasonable first order description of human behavior at the task. It is

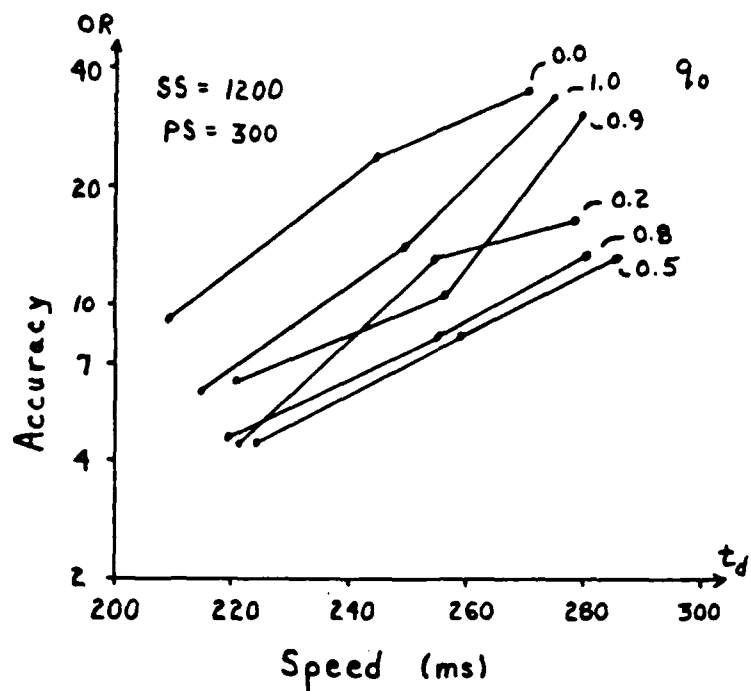


Figure B.6 Speed/Accuracy Data for Subject TK

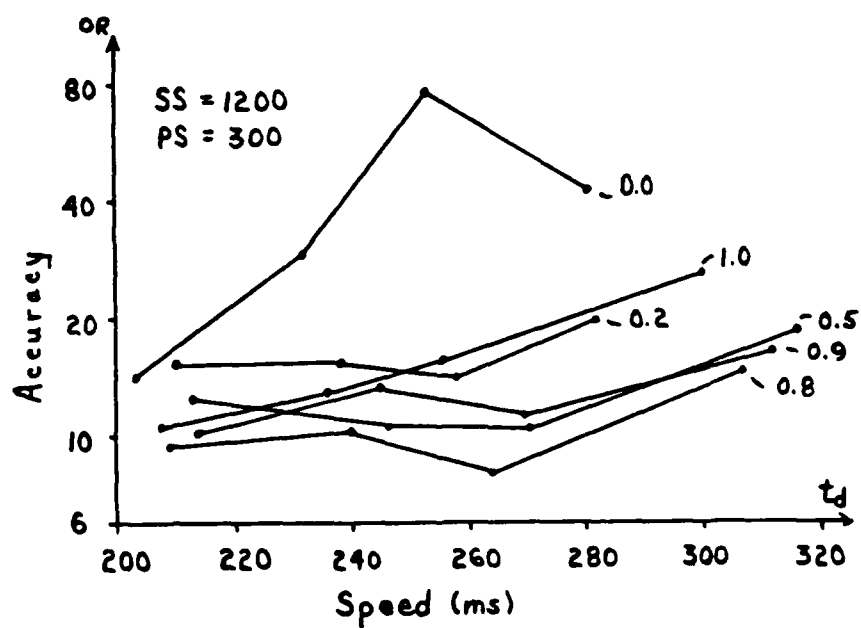


Figure B.7 Speed/Accuracy Data for Subject P0

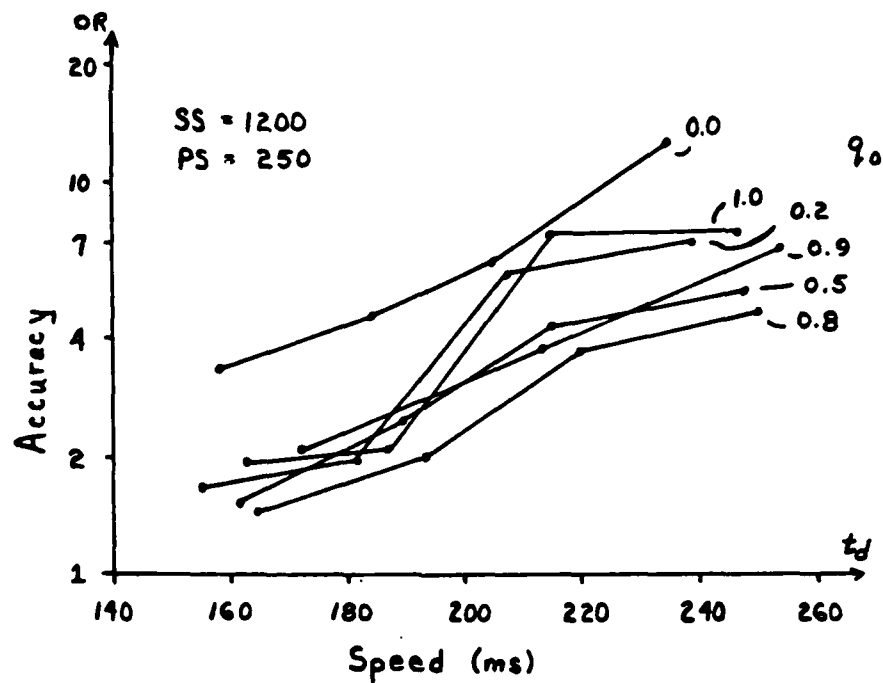


Figure B.8 Speed/Accuracy Data for Subject KB

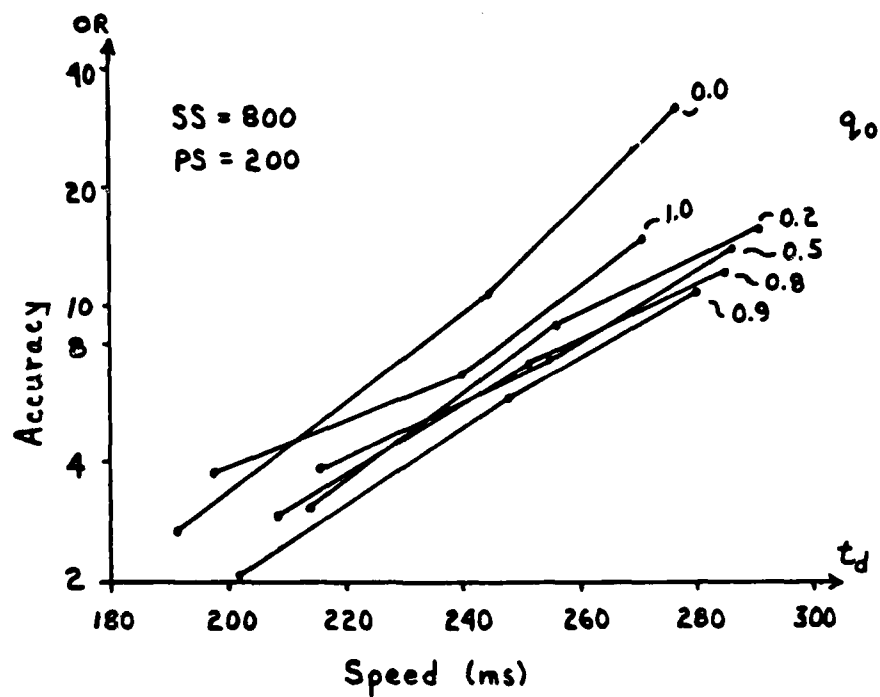


Figure B.9 Speed/Accuracy Data for Subject JK

also apparent that the value of q_0 parameterizes the level of accuracy. At $q_0 = 0$, where all vertical thresholds are used, accuracy is highest. As switching increases, up to $q_0 \approx 0.8$, accuracy declines. As q_0 continues on to 1.0 (all horizontals), however, there is some improvement in the general accuracy level. This characteristic can be explained directly in terms of the results shown in Figure B.5. The additional processing time required to switch between thresholds and the fact that horizontals take more time than verticals means that for a given t_d value, the degree to which a member is overloaded depends on q_0 .

Given the observed results, the following input/output description of human behavior is suggested for this task situation:

$$\bar{k}_2 : \text{ if } u = j \text{ and } \begin{cases} y_2 \geq t_{2j} & v = 1 \text{ wp } 1-q_2 \\ y_2 < t_{2j} & v = 0 \text{ wp } q_2 \end{cases} \quad j = 0,1 \quad (\text{B.15})$$

In words, threshold comparison tests are made correctly a fraction $1-q_2$ of the time, and an error is made on a fraction q_2 of the observations. The value of q_2 is related to the odds ratio, and therefore depends on q_0 and t_d . In particular, define the quantity f to be the natural logarithm of the odds ratio and generalize the definition of OR to be in terms of the probabilities of correct and incorrect responses:

$$f = \ln (\text{OR}) = \ln \left(\frac{\text{pr}(\text{correct})}{\text{pr}(\text{incorrect})} \right) \quad (\text{B.16})$$

Using eq.(B.16), the observed family of relationships between OR and t_d can be linearized and expressed analytically as

$$f = f_s(q_0) \cdot (t_d - t_c(q_0)) \quad (\text{B.17})$$

where f_s is the slope of a speed/accuracy locus and $t_c(q_0)$ effectively represents the t_d axis intercept. Since by definition

$$\text{pr}(\text{incorrect}) = q_2 \quad (\text{B.18})$$

eq.(B.16) and eq.(B.17) are related according to the expression

$$q_2 = \frac{1}{1 + e^f} \quad (\text{B.19})$$

The quantities f_s and t_c are parameters that must be chosen to best represent observed behavior. For the data given in Figures B.6-B.8¹, Table B.4 lists estimates for these parameters that have been calculated

Table B.4 Estimates of Speed/Accuracy Model Parameters

Condition (q_0)	Subject TK		Subject PO		Subject KB	
	f_s	t_c	f_s	t_c	f_s	t_c
0.0	0.0235	114	0.0117	- 35	0.0217	117
0.2	0.0229	151	0.0022	-1020	0.0190	130
0.5	0.0179	138	0.0043	- 325	0.0152	132
0.8	0.0174	133	0.0044	- 284	0.0142	137
0.9	0.0273	157	0.0042	- 352	0.0143	119
1.0	0.0291	154	0.0106	- 6	0.0209	136

using a least squares criterion. It is assumed that interpolation can be used to determine a value of q_2 for q_0 values that are between the conditions for which data was observed.

In calculating the model parameters for subject PO, the third point in the $q_0 = 0.0$ condition has been neglected as unrepresentative of the subject's behavior. Its exceedingly high OR value stems directly from a single run of 200 trials in which the subject was extremely consistent in response time and also highly accurate. Furthermore, it is questionable whether the accuracy level for the first partition of conditions 0.2 and

¹Because subject JK did not continue on as an organization member, an information processing model for him has not been completed. However, the data shown in Figure B.9 have been included as additional support for using the log-linear relationship between OR and t_d as the basis for the information processing model of the second member. Such support can be obtained from inspection of the figure.

0.5 are representative of actual tendencies. No adjustment has been made, however, and the values in Table B.4 include their effect.

In sum, the information processing model of the second member is taken to be that of eq.(B.15), where q_1 is determined as a function of q_0 and t_d . The particular model used to relate these quantities has been derived from the speed/accuracy characteristics observed as humans perform the task. Two characteristics of the model are implicit. First, it is assumed that changes in the thresholds t_{1j} do not affect the speed/accuracy loci. Subsequent operation of the organization will indicate that this is a reasonable assumption. Second, the speed/accuracy model is such that a particular accuracy level is associated with an exact speed of response. In a sequence of trials, however, each response will not be exactly the same speed. Rather, a distribution will be observed about some average speed. For present purposes, it will be assumed that, so long as response time distributions are narrow, it is valid to use the mean value of the response time distribution as the t_d value. The alternative is to use the response time distribution to compute an "expected value" of q_1 , which introduces needless complexity into the model.

B.3 Integration of Design Elements and Test of Design

The information processing models developed in the previous section can be viewed in two ways. On one level, they represent generic descriptions of human behavior at the respective tasks. On a second level, however, the models represent specific descriptions of how particular individuals have behaved when performing one of the tasks. Given the two viewpoints, integration of design elements into a nominal organization design can take place in either a general or specific fashion. Appendix A discusses the former. In this section, however, specific individuals will be paired as team members, and nominal organization designs will be determined and tested in terms of these specific teams.

B.3.1 Integration

A nominal design for the organization under consideration is obtained as the solution to Problem CNO:

Problem CNO

$$\begin{array}{ll} \min & \left\{ J_0 = \text{pr}(\text{detection error}) \right\} \\ t_1, t_{20}, t_{21} & \\ q_1 & \text{s.t. } T_{p1} \cdot (\tau_1)^{-1} \leq 1 \end{array}$$

Because the values of thresholds t_{2j} do not affect the accuracy of the second member, their placement depends only on the value of \bar{P}_2 , which is the joint distribution $p(u, H)$ (see Chapter 2). In fact, t_{2j} can be placed at their normative values. As a function of \bar{P}_2 , these values are given as

$$t_{20}^* = \frac{2(\sigma_2)^2 \log(p_{01}/p_{00}) + (m_{20})^2 - (m_{21})^2}{2(m_{20} - m_{21})} \quad (\text{B.20})$$

$$t_{21}^* = \frac{2(\sigma_2)^2 \log(p_{11}/p_{10}) + (m_{20})^2 - (m_{21})^2}{2(m_{20} - m_{21})} \quad (\text{B.21})$$

When the values of q_1^c and t_1^c are selected, \bar{P}_2 will be determined and consequently t_{20}^c and t_{21}^c as well.

From the above discussion, it is evident that the solution to Problem CNO reduces to searching over possible t_1 and q_1 values. Results from Appendix A sharply focus this search to include only those (t_1, q_1) pairs for which $q_1 = 0$ or for which $T_{p1} = \tau_1$. The former corresponds to the situation where t_1 is such that

$$\bar{t}_{\text{SCR}}(t_1) \leq \tau_1 \quad (\text{B.22})$$

The latter case occurs when

$$\bar{t}_{SCR}(t_1) > \tau_1 \quad (B.23)$$

and fast guessing is required to meet the workload constraint.

For the specific organizations to be considered, τ_1 is set at 260 ms. Because of individual member differences, no one single value of τ_2 has been used, and values of τ_2 vary between 230 and 260 ms. The solution to Problem CNO in all cases, however, is such that

$$q_1^C = 0.0 \quad (B.24)$$

$$t_1^C = -1.6 \quad (B.25)$$

This in turn implies that

$$t_{10}^C = 2.46 \quad (B.26)$$

$$t_{20}^C = -0.32 \quad (B.27)$$

The design solution in eq.(B.24)-eq.(B.27) has not resulted accidentally. In order to ensure that interesting and distinctive predictions about organization behavior could be made, values of parameters were chosen so that the nominal organization would have certain desired qualitative characteristics. In particular, τ_1 was chosen small enough so that a significant amount of fast guessing would be required if t_1 were left at t_1^* . Furthermore, the value of τ_2 and the relative fidelity of each member's observations have been selected so that it would be highly desirable for the second member to operate at the greatest possible accuracy level. Given these conditions, the optimal tradeoff is to minimize q_0 , which places t_1^C at -1.6. Indeed, if a valid model had been constructed for $t_1 < -1.6$, the optimization would have put t_1 at a still smaller value in order to decrease q_0 even further. As it is, however, the conditions selected will provide a rich enough set of test points that can be used to examine the methodology's viability.

B.3.2 Organization Operation and Test

Overview and General Procedure

This section presents the results obtained from operating the detection organization under several test conditions using various teams. Each test was conducted using the same general experimental procedure. A key feature of the procedure is that the operation of the first member is separated in time from that of the second member. This is possible because there is no feedback between organization members, i.e. there are no loops in the information flow of the organization. Among other things, the ability to decouple the organization simplifies the experimental setup by allowing the same equipment to be used for both members.

Given the experimental device of separating organization members in time, the process of conducting a test of organization operation proceeded as follows. First, a sequence of values that designate the underlying presence or absence of H was generated according to the distribution $(p_0, p_1) = (0.4, 0.6)$. The first organization member was then operated using this sequence and his responses were recorded. Recall that they can be of three types: left button pushed ($u=0$), right button pushed ($u=1$), or both buttons pushed.

At some later time, the second organization member was then operated. In doing so, the same H sequence was used as a basis for generating observations y_2 . Furthermore, the responses of the first member were used to select the threshold for the second member. Prior to actual operation, however, the experimenter assigned an interpretation to the first member's double-button pushes and thereby selected the fast guessing bias of the first member. Responses of the second member were then recorded as he was operated. Since they also represent detection decisions of the organization, they were later compared with the underlying H sequence to obtain the detection error rate realized by the organization.

In the following paragraphs, the three basic test conditions for each organization are outlined. Next, results of operating the first member are presented and discussed. Finally, specific organizations are formed, predictions about their behavior at the three test conditions are made, and results of operation of the organizations under these conditions are presented and discussed.

Test Conditions

To evaluate the ability of the methodology to predict operating behavior of an organization, three operating points have been selected for testing purposes. One is the nominal organization design point. At this point, fast guessing by the first member is predicted to be unnecessary and organization performance is (by definition) predicted to be better at this point than at any other feasible operating point. This condition is designated as Test Condition 1.

An additional pair of test conditions is obtained by leaving the thresholds of both members at their respective normative values. Since $\bar{t}_{SCR}(t_1^*) > \tau_1$, fast guessing is predicted to be necessary by the first member in this case. Moreover, the bias in guessing will presumably have an effect on the operation of the second member. If $g_1 = 0.5$, then as the fast guessing level increases the second member will tend to use each threshold on a more or less equal basis. If $g_1 = 0.0$, however, increases in fast guessing will tend to increase the relative usage of the vertical threshold. If the level of fast guessing is significant, there will be a noticeable difference in the effect of different g_1 values on the input/output processing accuracy of the second member (and also on organization performance). Since the value of g_1 is controlled by the experimenter, operating with $t_1 = t_1^*$, $t_{2j} = t_{2j}^*$, and $g_1 = 0.0$ or 0.5 represents a pair of realizable test conditions. Both of these conditions will be used as test points for organization operation.

The three test conditions are summarized in Table B.5. In general,

Table B.5 Organization Test Conditions

Number	Thresholds	FG Bias (g_1)
1	Nominal Design: $t_1^c, t_{2,1}^c$	0.5
2	Normative : $t_1^*, t_{2,1}^*$	0.0
3	Normative : $t_1^*, t_{2,1}^*$	0.5

the qualitative characteristics of organization operation are predicted to be as follows (the superscript designates the test condition):

$$q_1^c = q_1^1 = 0 \quad q_1^2 = q_1^3 \quad (\text{B.28})$$

$$q_2^1 < q_2^2 < q_2^3 \quad (\text{B.29})$$

$$J_0^1 < J_0^2 < J_0^3 \quad (\text{B.30})$$

Subsequent tests using specific individuals will assign values to the quantities in eqs.(B.28)-(B.30) against which observed results can be compared.

First Member Test Results

Because of the structure of the organization, it is possible to test the first member without activating the second. This has in fact been done using the two subjects for which information processing models were developed earlier. Data for each test was collected as follows. In previous sessions, subjects had become accustomed to operating under a rate constraint through a combination of instruction and experience. They were instructed to exercise their two processing options at their discretion, but to keep in mind that fast guessing had a high-leverage potential for reducing average processing time. They were also told that their main goal was to use the SCR option as much as possible without sacrificing the quality of SCR responses.

To reinforce these instructions, a payoff function was computed for each experimental run under a rate constraint. A reward of one cent was given for each correct SCR (i.e. each correct single-button response) and a penalty of 25 cents for each erroneous SCR. No reward or penalty accrued for a fast guess, and a substantial penalty (\$5) was assessed if the member fell behind in processing. Subjects were told that this penalty would not be assessed as long as the dial position was at 4 o'clock or above when the experimental run ended. For experimental runs of 100-200 trials, it was a considerable challenge to finish with a positive payoff. Although no money actually changed hands, the payoff function was successful in re-inforcing the verbal instructions given to the subject.

The specific tests of first member operation were conducted in the same respective sessions in which the data shown in Figure B.3 were obtained. Each subject was placed under a rate constraint of $\tau_1 = 260$ ms, which is the organization's interarrival time for observations. Each test conducted included two experimental runs. The first consisted of 100 trials and the second had 150. Results for the second run are shown in Table B.6. Several runs were made at each organization test condition. Note that Test Conditions 2 and 3 are the same from the first member's point of view. The second column in the table labels those runs that will be used later to complete the operation of the organization. Finally, in addition to the specific organization test conditions, data for an intermediate value of t_1 were obtained from subject PO.

A key consideration in the operation of the first member is whether the integrity of the two options is maintained under stress. From the data shown and by comparison with Table B.2, it is evident that this is the case. The subjects were able to exercise their options to realize an average time of 260 ms, yet the time taken on stimulus controlled responses remained near that observed when the rate constraint was not in effect. In particular, except for a small fraction on one test run, fast guessing was not required at $t_1 = -1.6$. Furthermore, the error rate when

Table B.6 First Member Operation

	TC		t_1	T_{p1}	SCR			FG	
					\bar{t}_{SCR}	σ_{SCR}	P_{SCR}	\bar{t}_{FG}	q_1
Subject MP	1	a	- 1.6	252	252	82	0.007	-	0.0
	1		- 1.6	260	263	82	0.021	173	0.03
	2,3	b	0.0	261	302	75	0.040	183	0.34
	2,3	c	0.0	264	329	88	0.063	192	0.47
	2,3		0.0	263	313	121	0.060	204	0.45
	2,3		0.0	262	305	73	0.011	195	0.39
Subject PO	1	d	- 1.6	252	252	87	0.020	-	0.0
	-		- 0.8	261	289	59	0.000	166	0.23
	-		- 0.8	259	280	81	0.008	162	0.19
	2,3	e	0.0	258	300	71	0.031	184	0.35
	2,3		0.0	262	305	32	0.009	156	0.39

using the SCR option did not change substantially. A certain variability in the average fast guessing time is evident, however. Since the fraction of fast guessing effectively depends on both \bar{t}_{SCR} and \bar{t}_{FG} , its value is sensitive to variations in both of these quantities. It happens, however, that this does not substantially affect either the predictions or results regarding organization operation.

Organization Test Results

To complete the test of organization operation, response sequences associated with the data in Table B.6 were used as inputs to the second organization member. Because of the decoupling of organization members, a number of combinations of individuals as teams could be readily tested. Table B.7 lists the organizations that were tested. They are designated by letter and are distinguished not only by their members, but also by the particular first member sequences used. Note that Organizations E and F represent two tests with the same members and also with the same first

Table B.7 Organizations Tested

		First Member (Sequences)		
		MP (a,b)	MP (a,c)	PO (d,e)
Second Member (Target τ_2)	TK (260)		A	B
	PO (230)		C	
	PO (240)			D
	KB (240)	E,F		

member sequences. In subsequent discussion, organizations will be referred to by a letter and by the test condition; for example A1 designates Test Condition 1 of Organization A.

Operation of the second organization member (and thereby of the organization) was conducted as follows. Based on the proficiency of the particular subject a "target" value of τ_2 was selected such that the member would be overloaded. The term target is used because exact control of T_{p2} was not possible due to the nature of the task situation. Regulation of response time was accomplished by choosing the "beep deadline" of the auditory mechanism in a judicious manner based on previously observed behavior at the task. That is, in the course of developing the information processing model, the average response time was observed to be less than the deadline by a reliable amount, typically about 30-40 ms. This characteristic was used to set the auditory mechanism's deadline with respect to the targeted τ_2 value on the premise that the realized T_{p2} would be near τ_2 . Targeted values of τ_2 have been included in Table B.7.

With the timing deadline selected, the thresholds for a given condition were set and the organization member was given the opportunity to adjust his operation in a preliminary run of 150 trials. A run of 450 trials followed, which constituted the test run of the particular

organization at the given condition. To obtain a first member sequence of 450, the recorded sequence of 150 trials was used three times in succession. All three test conditions for an organization were conducted in the same session.

Tables B.8-B.13 summarize the results of the tests for the six organizations formed. Columns designated "p" contain predicted values; those designated "o" contain observed values. Predicted values of q_0 are obtained using the first member's information processing model. Predicted values of q_1 have been obtained using the observed values of T_{p1} as the value of t_d in the second member's model. This was done to compensate for the experimental difficulty in regulating the second member's processing time, even though the target values of τ_1 were substantially realized using the technique described earlier. Finally, in the predicted values of q_1 and J_0 the last digit has been included as an indication only; three-place accuracy is not implied or claimed.

Table B.8 Organization A Test Results

TC	q_0		T_{p1}	σ_1	q_1		J_0	
	p	o			p	o	p	o
1	0.065	0.050	256	97	0.048	0.098	0.121	0.171
2	0.21	0.20	265	80	0.069	0.069	0.145	0.149
3	0.45	0.41	258	84	0.098	0.144	0.171	0.169

Table B.9 Organization B Test Results

TC	q_0		T_{p1}	σ_1	q_1		J_0	
	p	o			p	o	p	o
1	0.065	0.040	258	54	0.048	0.067	0.121	0.127
2	0.31	0.27	262	71	0.083	0.078	0.145	0.142
3	0.44	0.44	258	54	0.098	0.104	0.169	0.156

There are eighteen runs of 450 trials included in Tables B.8-B.13. All but two of them represent tests in which the second member was operating in the same mode and frame of mind that was apparent when the information processing model was developed. The exceptions are A1 and A3, which were the last runs that subject TK completed. Fatigue and eagerness to quit were apparent at that time and are also evident in the data.

In considering the results shown in the tables, there are two comparisons to be made. The first is whether the observed values match those that were predicted from the models. The second is whether observed values are in the relative order predicted. Except for the anomalies of Organization A, the relative ordering is as predicted in all cases. This is particularly significant with respect to the organization's performance, since it indicates that the nominal design selected by the methodology does in fact have superior performance than if thresholds were assigned their normative values.

Of the six organizations tested, the results for B are perhaps the most encouraging overall, both in relative and absolute terms. There is a clear separation in the performance observed for the three test conditions, which matches well with the absolute values predicted.

Consider now Organizations C and D, which both used Subject PO as the second member. There is somewhat less agreement, in absolute terms, of predicted and observed results. This can be explained as follows. A generally higher q_2 value than predicted has been observed across all conditions in both of these organizations. This suggests that the model for PO is not representative of actual behavior. A review of Figures B.6-B.9 indicates that Subject PO's information processing model is perhaps the least accurate, and that further refinement might be warranted.

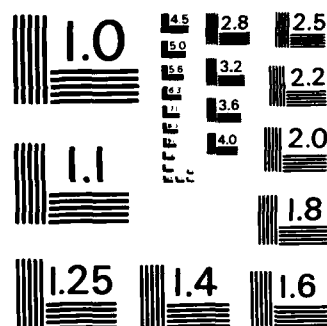
The discrepancy in predicted and observed performance values for organizations C and D is due largely to the increase in q_2 . From Appendix A, it is known that J_0 can be written as

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Table B.10 Organization C Test Results

TC	$p \quad q_o \quad o$		$T_{p2} \quad \sigma_2$		$p \quad q_2 \quad o$		$p \quad J_o \quad o$	
1	0.065	0.050	227	40	0.050	0.071	0.123	0.156
2	0.21	0.20	235	42	0.059	0.096	0.137	0.187
3	0.45	0.41	233	36	0.077	0.100	0.154	0.189

Table B.11 Organization D Test Results

TC	$p \quad q_o \quad o$		$T_{p2} \quad \sigma_2$		$p \quad q_2 \quad o$		$p \quad J_o \quad o$	
1	0.065	0.040	229	39	0.050	0.053	0.123	0.142
2	0.31	0.27	238	44	0.066	0.087	0.130	0.158
3	0.44	0.44	240	49	0.074	0.100	0.138	0.182

Table B.12 Organization E Test Results

TC	$p \quad q_o \quad o$		$T_{p2} \quad \sigma_2$		$p \quad q_2 \quad o$		$p \quad J_o \quad o$	
1	0.065	0.050	233	45	0.091	0.064	0.157	0.153
2	0.22	0.31	240	47	0.110	0.096	0.179	0.178
3	0.47	0.44	243	55	0.150	0.156	0.214	0.196

Table B.13 Organization F Test Results

TC	$p \quad q_o \quad o$		$T_{p2} \quad \sigma_2$		$p \quad q_2 \quad o$		$p \quad J_o \quad o$	
1	0.065	0.050	241	41	0.078	0.053	0.147	0.140
2	0.22	0.31	249	51	0.096	0.100	0.156	0.182
3	0.47	0.44	237	49	0.160	0.160	0.211	0.200

$$J_0 = (1-2q_2) \cdot J + q_2 \quad (B.31)$$

where J is fixed for given t_{2j} values and given behavior of the first organization member. Its value is on the order of 0.1. Thus, according to eq.(B.31), any variation in q_2 will appear approximately as an additive variation in J_0 . In view of this, comparison of the differences in the p and o columns of J_0 with corresponding differences for q_2 in Organizations C and D indicates that this effect is indeed evident in the result observed, and furthermore accounts for a significant fraction of the J_0 differences.

For Organizations E and F, in which the author was the second member, it is worth noting to what degree the predicted results could be manufactured. With respect to input/output errors it is certainly true that the desired relationship of q_2 can be kept in mind as the task is being performed. However, it is also true that in a run of 450 trials (about 8 minutes long), one easily loses track of the beginning, cannot anticipate the end and has a good deal of difficulty in counting errors while trying to concentrate on the task. Moreover, the organization's performance cannot be inferred except by analysis that occurs following the run. Therefore, the incentive is for Subject KB to operate as consistently as possible in order to achieve a fair test. Also, as mentioned earlier, the author is by far the most practiced of any of the subjects. This includes an earlier test of the organization using a run of 300 trials at each condition, which proved inconclusive because it was too short.

Taken as a whole, the results that have been obtained substantially agree with those predicted. The first organization members were able to maintain the integrity of their options under stress. In particular, fast guessing was not required for nominal organization operation. Given the conditions established by the first member for the second, the latter operated as anticipated. In particular, variation with respect to q_2 in the second member's behavior was relatively as predicted. Both of these results attest to the validity of the information processing models for

each member. More importantly, however, is that the organizations have been observed to perform as predicted. This lends support to the conclusion that the design approach itself is valid.

REFERENCES

- [1] T.B. Sheridan and W.R. Ferrell, Man-Machine Systems, Cambridge, MA: MIT Press, 1974.
- [2] R.R. Tenney and N.R. Sandell, "Structures for distributed decision-making," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-11, no. 8, pp. 517-527.
- [3] R.R. Tenney and N.R. Sandell, "Strategies for distributed decision-making," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-11, no. 8, pp. 527-538.
- [4] Y-C. Ho, "Team decision theory and information structures," Proceedings of the IEEE, Vol. 68, no. 6, pp. 644-654.
- [5] J. Marschak and R. Radner, The Economic Theory of Teams, New Haven, CT: Yale University Press, 1972.
- [6] Y-C. Ho and K-C. Chu, "Team decision theory and information structures in optimal control problems — part I," IEEE Transactions on Automatic Control, Vol. AC-17, no. 1, pp. 15-22.
- [7] L.K. Ekchian, "Optimal Design of Distributed Detection Networks," Ph.D. thesis, MIT, Cambridge, MA, 1982.
- [8] N.R. Sandell, P. Varaiya, M. Athans, and M. Safonov, "Survey of decentralized control methods for large scale systems," IEEE Transactions on Automatic Control, Vol. AC-23, no. 2, pp. 108-128.
- [9] H.A. Simon, "A behavioral model of rational choice," Quarterly Journal of Economics, Vol. 69, pp. 99-118.
- [10] J.G. March and H.A. Simon, Organizations, New York: Wiley, 1958.
- [11] J.R. Galbraith, Organization Design, Reading, MA: Addison-Wesley, 1977.
- [12] J.D.W. Morecroft, "System dynamics: portraying bounded rationality," Omega, March, 1983.
- [13] R. Vesson, F. Hayes-Roth, et.al., "Network structures for distributed situation assessment," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-11, no. 1, pp. 5-23.
- [14] R. Smith and R. Davis, "Frameworks for cooperation in distributed problem solving," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-11, no. 1, pp. 61-70.
- [15] R.W. Bailey, Human Performance Engineering: A Guide For System Engineers, Englewood Cliffs, NJ: Prentice-Hall, 1982.

- [16] B.H. Kantowitz and R.D. Sorkin, Human Factors: Understanding People-System Relationships, New York: J. Wiley and Sons, 1983.
- [17] E.J. McCormick and M.S. Sanders, Human Factors in Engineering and Design, New York: McGraw-Hill, 1982.
- [18] A.F. Sanders, "Some remarks on mental load," in Mental Workload: Theory and Measurement, N. Moray, ed., New York: Plenum Press, 1979.
- [19] E.P. Soulsby, "Human Operator Workload: A Survey of Concepts and Assessment Techniques," Technical Report EECS TR-82-4, University of Connecticut, Storrs, CT, 1982.
- [20] N. Moray, ed., Mental Workload: Theory and Measurement, New York: Plenum Press, 1979.
- [21] R.W. Pew, S. Baron, C.E. Feehrer and D.C. Miller, "Critical Review and Analysis of Performance Models Applicable to Man-Machine Systems Evaluation," Report no. 3446, Bolt, Beranek and Newman, Inc. Cambridge, MA.
- [22] W.B. Rouse, Systems Engineering Models of Human-Machine Interaction, New York: North Holland, 1980.
- [23] D.M. Green and J.A. Swets, Signal Detection Theory and Psychophysics, New York: Wiley, 1966.
- [24] S. Baron, G. Zacharias, R. Muralidharan and R. Lancraft, "PROCRU: A Model For Analyzing Flight Crew Procedures in Approach to Landing," NASA CR-152397, 1980.
- [25] N.E. Lane, M.I. Streib, F.A. Glenn and R.J. Wherry, "The human operator simulator: an overview," in Proceedings of Conference on Manned Systems Design, 1980, pp. 1-39.
- [26] K.L. Boettcher, "A procedure-based approach to human information processing models," Laboratory for Information and Decision Systems, LIDS-P-1499, MIT, Cambridge, MA, 1985.
- [27] H.L. Van Trees, Detection, Estimation and Modulation Theory, Vol.I, New York: John Wiley, 1968.
- [28] J.I. Yellot, "Correction for Fast Guessing and the Speed-Accuracy Tradeoff in Choice Reaction Time," Journal of Mathematical Psychology, Vol.8, 1971, pp. 159-199.
- [29] R.W. Pew, "The Speed-Accuracy Tradeoff," Acta Psychologica, Vol. 30, 1969, pp. 16-26.
- [30] D.G. Luenberger, Introduction to Linear and Nonlinear Programming, Reading, MA: Addison-Wesley, 1973.

- [31] R.G. Swenson, "The elusive tradeoff: Speed vs. accuracy in visual discrimination tasks," Perception and Psychophysics, 1972, Vol. 12, pp. 16-32.
- [32] J.S. Lappin and K. Disch, "The Latency Operating Characteristic: I. Effects of Stimulus Probability on Choice Reaction Times," Journal of Experimental Psychology, 1972, Vol. 92, no. 3, pp. 419-427.

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